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POST-MORTEM IDENTIFICATION OF MEAT WITH ABNORMAL AUTOLYSIS BY NON-INVASIVE METHODS

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Abstract
The theme under consideration is of great interest for researchers and practical specialists engaged in the development of methods for identification of meat with different courses of autolysis. In this review, modern non-invasive methods for meat quality assessment are presented. The authors describe methods developed for identification of meat with nontraditional course of autolysis, including determination of electric properties of meat (electrical conductivity, electrical resistance, electrical impedance), optical methods (light scattering, reflection, absorption, Raman spectroscopy, fluorescence spectroscopy, visible/near/mid-infrared spectroscopy), investigation of physical parameters of meat (determination of meat color coordinates using spectrocolorimeters, nuclear magnetic resonance, ultrasound spectroscopy and others). The results of studies carried out by various researchers on the use of the proposed methods for meat sorting into quality groups and certainty of the obtained data are presented. It is shown that meat quality can be predicted using the obtained values of electrical parameters and optical spectra. Analysis of published materials shows that up to now there is no definite answer to the question about a choice of a method for identification of meat quality group. This problem requires further research and discussion.

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Introduction

Modern conditions of intensive raising of farm animals as well as target action of genetic transformations lead to formation of specific features of meat quality. For more than fifty years, the efforts of scientists and specialists in the field of meat production and processing are aimed at establishing all factors that cause predisposition of animals to stress, assessing a degree of their negative effect on the development of deviations in meat quality. Along with the problem of assessment of causes that induce quality peculiarities of meat raw materials, there is a problem of identification of meat with abnormal course of autolysis with the purpose of its rational use [1]. The objective determination of meat quality indicators requires labor-consuming laboratory investigations and the results of analyses can be obtained after several days. Joo et al. [2] stated that a method for effective grading of carcasses should be economical, easy to use and provide information as soon as possible after animal slaughter.

According to the opinion of many researchers [3–6], the most accessible and reliable method of meat grading into quality groups is measuring pH of muscle tissue of hot carcasses (pH_{45}) and then 24 hours after animal slaughter (pH_{24}). Comparison of the pH_{45} and pH_{24} values enables detecting meat with abnormal development of autolysis and identifying NOR, PSE and DFD quality groups. The rate of pH decline over a day of autolysis allows relatively accurate sorting of meat into quality groups. However, this method is quite labor-consuming as it requires certain expenditures on organization of pH measurement in carcasses after a day of holding. In addition, this method cannot be applied for assessing quality of meat in cuts.

Over the last years, scientists have focused their attention on the development of methods that make it possible to assess quality characteristics of meat already at the moment of measurements. As a result, many non-invasive methods have been developed. These methods are based on measuring electrical properties, optical characteristics and physical properties of meat.

It is possible to assess quality characteristics of muscle tissue by measuring its electrical conductivity [7], electrical resistance and electrical impedance [8]. Possibilities of meat quality identification by measuring its optical parameters (light scattering, reflectance and absorption) were demonstrated in [9,10]. Brøndum et al. [11], Hoving-Bolink et al. [12], Barbin et al. [13], Andersen et al. [14] have developed spectrophotometric methods for meat quality assessment. Methods of spectrometric determination of color coordinates, nuclear magnetic resonance, ultrasound spectroscopy are considered quite acceptable from the point of view of their use in practice [15–17]. During the last years, the interest of researchers to the development of the sensory technology for meat quality determination has been growing [18]. These methods are preferable as they are non-invasive.

The aim of this paper is to examine and compare non-invasive methods for identification of meat with abnormal course of autolysis and reveal advantages and disadvantages of each of them, which will allow seeing trends to understand the development of this theme.

Objects and methods

This review includes publications that present results of experimental investigations and review papers of national and foreign authors published from 1928 to 2022. The search included databases of search systems, such as eLibrary, CyberLeninka, Google Scholar, ScienceDirect, Springer open, PubMed, using keywords such as meat autolysis, quality group, electrical conductivity, optical methods, fluorescence spectroscopy, physical methods. In addition, leading Russian and foreign journals on the direction "Meat science" were used, publications in the Proceedings of the International conferences and bibliography from references lists were studied. One hundred fifteen sources were chosen. Criteria for selection of publications were relevance, practical significance, indexing in Russian and international scientometric databases.

Electrical conductivity methods

The main electrical properties of muscle tissue include its electrical conductivity, electrical resistance, and electrical impedance. Electrical properties of meat have been studied for a long time for many reasons, including the possible use for meat quality assessment [6,19–21]. As a result of investigations, it has been established that measuring electrical characteristics of meat is expedient for its quality identification. Thus, Antosik et al. [22] obtained relatively high coefficients of correlation between electrical conductivity and quality traits of meat from different animal groups. According to their data, measurement of this parameter in pork allows revealing PSE and DFD carcasses.

To predict pork quality, Oliver et al. [23] и Guerrero et al. [24] used electrical impedance spectroscopy (EIS). Impedance spectroscopy is based on the measurement of electrical conductivity of a sample under study when weak alternating currents with various frequencies are passed through it [25]. It is known that a live muscle is a poor conductor as intracellular and extracellular fluids are separated from each other by membranes [26]. Intact muscle tissue has low values of conductivity. As a result of disturbance of the state of cell membranes, redistribution of tissue fluid takes place, which directly influences a value of its electrical conductivity. The authors established that with an increase in the time of meat autolysis, cell membranes lose their semipermeability, and electrical conductivity tends to the maximum value.

Pliquett et al. [27] proposed using the parameter of electrical impedance P(y) for assessment of integrity of cell membranes and meat quality. The results obtained correlate well with a pH value and drip losses during autolysis, which enables differentiating NOR and PSE meat. The researchers found that the P(y) indicator gives the most significant results within a period of 4 to 24 hours of autolysis.

Egelandsdal et al. [28] also state that measurement of impedance directly reflects damages of the cellular structure of meat and allows judging about drip losses.

According to data of Suliga et al. [29], it is possible to assess a wide spectrum of morphological and physiological parameters of pork carcasses and reveal quality defects using bioimpedance analysis. The authors established the interrelation between physico-chemical indicators of meat quality (ultimate pH, color characteristics in the CIE L*a*b* system, drip losses) and results of the bioimpedance analysis. To compare defects of meat quality revealed using bioimpedance and physico-chemical indicators, the authors carried out proteomic analysis, which showed that differences in meat quality are reflected by the condition of eleven proteins that characterize meat quality.

Recently, EIS has found wide application for assessment of quality and safety of food products, including meat products.

It is known that electrical conductivity of biological tissues depends on the presence of various ions in cellular fluid. During autolysis, an increase in meat electrical conductivity is facilitated not only by the disruption of cell membranes and redistribution of tissue fluid, but also by protein destruction under the effect of tissue proteases as a result of rupture and fragmentation of myofibrils and degradation of cytoskeleton. With that, as Kristensen and Purslow [30] believe, ions migrate into intracellular space increasing conductivity of tissues.

According to data of Antosik et al. [22], to assess meat quality, electrical conductivity of muscle tissue can be measured both 1–3 hours and 24 hours after slaughter, when the rate of autolytic changes is slowed down and pork quality is forming.

Borzuta et al. [31] and Czyżak-Runowska et al. [32] suppose that measurement of electrical conductivity of meat 24 hours after animal slaughter correlates to a higher degree with meat parameters under study compared to measurements carried out after 90 min. Łyczyński et al. [33] hold the same viewpoint and state that measurement of electrical conductivity of pork 24 hours after slaughter can be used in practice to diagnose its quality.

To identify pork quality group (PSE, DFD, RFN) in the post-mortem period, Castro-Giráldez et al. [34] suggest determining dielectric spectra of muscle tissue from 100 Hz to 0.4 MHz in parallel and in perpendicular to the direction of muscle fibers. Notable differences in the permittivity between groups were observed 24 and 48 hours after slaughter. The authors assume that determination of dielectric properties of muscle tissue can be carried out 24 hours after slaughter to reveal meat quality group.

According to data of other researchers [35], determination of electrical conductivity of pork enables dividing semi-carcasses into PSE and DFD groups when measuring the parameter in the first 45–50 min. after slaughter.

Dielectric properties of meat with different character of autolysis were studied by Zakharov and Sus [36,37]. The authors found that, one hour after slaughter, electrical conductivity of m. *longissimus dorsi* of PSE pork was 6.83 mS/cm, while this parameter was equal to 4.73 and 3.39 mS/cm in NOR and DFD pork, respectively. The values of electrical conductivity of the studied muscle were 7.41, 5.29 and 3.73 mS/cm in PSE, NOR and DFD meat, respectively, after 24 hours of autolysis. Based on the results obtained, the authors proposed a method for meat sorting into quality groups according to the value of electrical conductivity.

According to Richer et al. [38], a rapid and convenient method for detection of DFD meat is a method of measuring rectangular electric pulse (h parameter), which allows making conclusion about structural changes in muscle tissue. The authors believe that it is possible to characterize the state of meat structure with high confidence using indicators pH, R (ratio of ATP to IMP concentrations) and h with data of electronic microscopy. It is shown that the specific features of autolysis of PSE meat are manifested in a rapid decrease in the value of pH and R and a reduction in the h parameter. The dependence between the rate of lactic acid accumulation and changes in tissue structure was established by optical methods.

Optical methods

The ability of muscle tissue to scatter the light flux is based on differences in the muscle fiber packing density in meat structure. Unlike NOR muscle tissue, PSE meat is characterized by looser fiber packing, which absorbs light better, and is perceived by the eye as lighter meat. On the contrary, DFD meat is characterized by tighter myofibrillar packing, reflects light less and is visually assessed as darker. Thus, assessment of color characteristics of meat enables determining its quality group quite confidently.

Raman spectroscopy can be considered one of the available spectroscopic methods for meat quality assessment. It is based on inelastic scattering of monochromatic light usually from a laser in visible, infrared or near ultraviolet spectra. It is also possible to use X-ray irradiation [39–41].

Raman light scattering was discovered in 1928 [42] and named after one of the authors (effect of Ch. V. Raman). The researchers described light scattering in liquids. Independently of them, in the same year in the Soviet Union, physicists G. S. Landsberg and L. I. Mandelshtamm recorded the similar light scattering in quartz independently of each other [43]. Preferability of this method consists in its ability to give information about concentration, structure and interaction of biomolecules inside intact cells and tissues (*in situ*) by the non-invasive method.

As regards meat quality assessment, this method enables determining its characteristics indirectly using correlations between one or several biophysical indicators and sensory properties. Herrero [44] established that the results of Raman spectroscopy correlate with data obtained by the traditional methods of meat quality assessment, such as protein solubility, viscosity, water holding capacity, structural-mechanical characteristics, peroxide value, fatty acid composition. The author believes that Raman spectroscopy can be applied for prediction of functional properties of proteins in situ and sensory indicators of meat products.

Results obtained by Scheier et al. [45] indicate that conversion of glycogen into lactic acid and degradation of ATP to IMP can be revealed using Raman spectra of pork obtained immediately after animal slaughter. The authors are of the opinion that it is possible to identify meat raw materials with abnormal course of autolysis at the early stages of autolysis with the help of Raman spectra.

Scheier et al. [45] и Bauer et al. [46] demonstrated that using Raman spectroscopy it is possible to classify meat into five quality groups (PSE, PFN, RFN, RSE, and DFD) both at the early stages of autolysis (from 0.5 to 10 h) and 24 hours after animal slaughter. It is also possible to reveal meat with signs of oxidative spoilage. The authors established that several indicators of quality, such as pH24, lightness L*, drip losses and meat hardness (shear force), can be predicted using this method 24 hours after animal slaughter.

Nache et al. [40] showed that values of pH_{45} и pH_{24} can be predicted with the help of Raman spectra measured 1–2 h and 24 h after animal slaughter. This is of great interest for the meat industry for the rapid assessment of meat quality by the non-destructive method.

By now, it has been established that Raman spectroscopy provides insights into changes in the protein structure [47,48], water holding capacity of meat [44], shear stress [49,50], changes in lipids [51]. Scheier et al. [45] demonstrated that it is possible to detect degradation of glycogen to lactic acid and ATP to IMP by the use of Raman spectra.

Schmidt et al. [52], Scheier et al. [53], and Andersen et.al. [54] stated that the development of a portable device made it possible to assess pork quality, which correlated with the ultimate pH and drip losses, using Raman spectra obtained between 30 and 120 min. after animal slaughter. The possibility of prediction of pH_{45} and pH_{24} values, as well as drip losses, in pork during post-mortem storage employing a portable Raman system was confirmed by [53,55]. Raman spectra of muscles obtained from the signals of glycogen, lactic acid, creatinine, ATP, ADP and phosphate group correlated well with the indicators mentioned above. According to the opinion of Osborne [56], PSE meat can be revealed using this method, which is promising for introduction into slaughterhouses.

Methods of infrared spectroscopy

To predict quality characteristics of meat, several authors [16,56–58] suggest using electromagnetic radiation in near-, mid- and far-infrared regions, which interacts with an object under study and the infrared spectra (IR-spectra) obtained are processed to obtain necessary information about meat quality.

IR-spectroscopy in the near-infrared region of radiation (NIR — near-infrared spectroscopy) is based on the absorption of infrared radiation with wavelengths of 700 to 2500 nm, or from 12 800 to 4000 cm^{-1} by a sample under study. According to data of Sahar et al. [59], spectra can be registered by means of an optical sensor on the open surface of a carcass in the area of chuck or round 1 h and 2 h after animal slaughter.

Multiple studies [60–65] demonstrated the possibility of using near-infrared spectroscopy to identify pork properties and differentiate it into quality groups.

Neyrinck et al. [64] and Kennedy et al. [65] suppose that the use of NIR-spectroscopy for pork sorting into NOR and PSE groups is possible at wavelengths of 4500 to 9500 cm^{-1}. The authors established that NIR-spectroscopy ensures high confidence of results of detecting PSE pork 24 hours after slaughter (90–93.3 %).

Pankratova et al. [66] and Monroy et al. [67] showed that the non-destructive spectral method of the control in the visible and near-infrared regions in a wave range from 350 to 2500 nm with the use of discriminate analysis enables identification of five pork quality groups (NOR, RFN, PSE, RSE and DFD) with the accuracy of 79 %.

According to the data of Prieto et al. [68], spectroscopy in the near-infrared range of 350–2500 nm (Vis-NIR) can be used to classify beef carcasses into DFD and NOR. The method makes it possible to reliably classify up to 95 % of carcasses.

Cafferky et al. [69] made a conclusion that the method of infra-red spectroscopy can be applied to predict quality indicators in beef both at the early and later (24–48 h) stages of autolysis.

To detect meat with quality defects (PSE и DFD), the authors [70,71] recommend employing infrared thermography of the porcine skin surface. Temperature measurement was carried out with a portable radiometer "Raytek11" at a distance of about 60 cm above the surface of porcine back immediately before their stunning. Based on the results of the investigations, the authors established that when a temperature of the surface of animal skin rose from 21.1 to 35 °C, the probability of occurrence of PSE and DFD meat increased. Thus, at a temperature of more than 32.2 °C, about 73 % of studied animals gave PSE and DFD pork after cutting with approximately the same proportion. With that, 6 % of pork showed moderate PSE properties, 39 % was PSE pork, 22 % was meat with moderate DFD properties and 33 % was DFD pork. At indications of the device lower than 26.5 °C, most animals gave NOR meat. When a skin surface temperature was 29.4 % meat tended to PSE.

According to the opinion of other researchers [68,72–74], this method has limited possibilities for assessment of meat properties, which is conditioned by meat heterogeneity. However, this method allows direct or indirect qualitative and quantitative assessment of chemical, physical and physico-chemical characteristics of an analyzed object, including pH (Prieto et al. [73]), color (Cecchinato et al. [75]), water holding capacity (Ripoll et al. [76]) and tenderness of meat (Leroy et al. [77]).

Čandek-Potokar et al. [78] demonstrated a possibility of application of near-infrared spectroscopy to determine pH, color parameters (L*, a*and b*), drip losses in pork during autolysis 24 h and 48 h after animal slaughter. Meat samples were scanned in a wavelength range of 400–2500 nm using a NIR Systems spectrophotometer model 6500. For the development of models and calibration, the method of partial least squares was used. The best calibrations were obtained for the meat samples in a spectral range of 400–1100 nm. According to authors' opinion, it is necessary to improve methods, which are used to calibrate data obtained by spectroscopy, and/ or their accuracy to improve the method of near-infrared spectroscopy.

Brøndum et al. [79] compared data on prediction of drip losses in pork in visible and near-infrared regions of reflectivity with low-voltage nuclear magnetic resonance spectrometry (NMR). The best results were obtained with the use of NMR.

However, there are not so many studies devoted to application of near-infrared spectroscopy to assess technological properties of meat. They suggest that first of all the results of different studies differ significantly from each other and, secondly, prediction of quality characteristics of meat with the application infrared spectroscopy is less accurate compared with the prediction of the chemical composition of meat.

Spectrocolorimetric methods

It is known that the color of an opaque body is conditioned by the spectral composition of light flux reflected from it. At present, the spectrocolorimetric method of small color differences in the uniform color space system CIE L*a*b* is used to assess meat color. The CIE L*a*b* color space is an international standard for color measuring adopted by the International Commission on Illumination (CIE) in 1976. L* is the lightness coordinate, which varies from 0 to 100 (from black to white) and coordinates a* (from green if negative to red if positive) and b* (from blue if negative to yellow if positive) are chromatic components, which vary from –120 to +120 [80].

In 1931, the International Commission on Illumination (CIE) published color spaces CIE XYZ 1931, which determine interrelation between the visual spectrum and visual sensation of particular colors with the help of the human color vision.

All know colors are developed from various ratios of three spectral colors: red (700 nm), green (546.1 nm) and blue (435.8 nm). According to data of McDarrah et al. [81], each color is characterized by hue, saturation and lightness but is not a physical quantity and therefore does not have a unit of measurement. As Klettner et al. [82] showed, hue is a characteristic, which distinguishes achromatic (black, white and gray) color from chromatic. Saturation characterizes a ratio of colorfulness to brightness that is it is the highest for spectral colors. Brightness is determined by the content of black and white colors.

Analyzing various methods for meat quality assessment, Chizzolini et al. [83] и Kudryashov et al. [84] proposed to identify PSE и DFD meat by the spectrophotometric method, determining values of color coordinates: L* — lightness, a* — redness, b*- yellowness and H — hue. The quantitative assessment of color intensity can be used as a basis for meat classification into quality groups depending on the character of autolysis [85,86]. Results obtained when determining color in the L*a*b* system allowed collecting a large databank of color characteristics of different meat products [86,87].

McKee and Sams [88] established the correlation between a pH value of poultry meat and the lightness value (L*). A pH decrease by 0.2–0.3 units in poultry meat is accompanied by an increase in the lightness (L*) value by 3–4 units.

Owens et al. [89] believe that color evaluation is the most rapid and available method of meat quality assessment for manufacturers of meat products and it is easy to perform both visually and instrumentally using optical scanning.

Kudryashov et al. [90] developed a method for identification of NOR, PSE and DFD meat using measurement of a ratio between the reflection intensity of the light flux of a sample under test and that of the reference (T) using a color comparator KTsSh (KTsZ). Comparison of their values allows determining to which quality group meat belongs. Thus, when the T value is lower than 1.100 and higher than 1.050 meat corresponds to NOR, when T is less than 1.250 and more than 1,200 meat has DFD properties, and when T is less than 0.950 and more than 0.900 meat is classified as PSE.

Computer technologies

To identify PSE and DFD pork and beef, Tomasevic [91] proposed to use computer technologies, in particular, methods of digital processing of images based on registering changes in color characteristics of meat, meat extract and broth. It has been established that images of PSE and DFD meat differ significantly from NOR meat by color characteristics. Results can be used to develop a method for identification of different meat quality groups.

Sun et al. [92] developed a computer vision system (CVS) for objective color assessment in pork loin to determine its correspondence to the requirements of the industry. Based on the artificial intelligence, a model for prediction of pork quality groups by color has been created. The results show that the accuracy of prediction of pork quality using CVS achieves 92.5 %.

Girolami A. et al. [93] showed a possibility of applying the computer vision system (CVS) to assess quality of beef, pork and chicken meat. The authors found that the digital values of samples displayed on the monitor were more similar to the color generated by the computer vision system than to the color obtained using the Minolta CR-400 colorimeter. The authors believe that the CVS method gives more reliable data of meat color measurement than a colorimeter. Therefore, this method can be recommended for revealing quality of meat with abnormal autolysis.

Chmiel et al. [94] applied the computer vision system (CVS) to identify DFD beef. L*, a* и b* coordinates were determined using the CIELab and CVS systems. Also, the total content of heme pigments was determined. The results obtained using CIELab and CVS characterized DFD meat as darker than normal beef. Beef with lower content of heme pigments was lighter compared to beef with the high level of heme pigments. The authors suppose that the CVS method can be employed to determine DFD meat.

The computer vision system (CVS) was applied to reveal PSE pork using color parameters [95]. The authors found differences between PSE and RFN meat in terms of lightness (L*). According to the data of the authors, however, the coefficients of correlation and determination between color parameters characterized by lightness had low values of 0.44 and 19.4 %, respectively. A significant spread of results of color parameters obtained for certain meat quality groups indicate a limited possibilities of using the CVS method for classification of pork carcasses using the *Semimembranosus* muscle.

Comparative data on the color of pork loin obtained by Sun et al. [96] with the use of the computer vision system and colorimeter Minolta indicate a significant correlation ($P < 0.0001$) of lightness L* (0.91), redness a* (0.80) and yellowness b* (0.66) values recorded using these methods. To assess results of predicting coordinates of pork color based on the artificial intelligence, two regression models were developed. These models enable on-line identification of meat quality group by color. The authors showed that the highest accuracy of predicting pork color characteristics is achieved using the CVS method, which corroborates data obtained by Girolami et al. [93].

The use of the computer vision system (CVS) makes it possible to acquire information both about external characteristics and the internal structure of an object under investigation. To confirm meat quality characteristics measured by CVS, the authors [97,98] carried out meat classification by pH_{45} and pH_{24}, electrical conductivity, drip losses, water binding capacity and color in the CIEL*a*b* system. The most accurate classification was recorded when determining color parameters (hue, saturation, lightness). It has been established that using the CVS method it is possible to identify PSE and DFD meat but it is not possible to differentiate RSE from RNF. In conclusion, the authors believe that the computer vision system can be used for rapid analysis of pork (m. *longissimus lumborum*) quality under industrial conditions.

Physical methods

The specific features of structure and condition of proteins, amino acids, nucleotides, lipids, organic acids, water and other substances in the composition of meat of different quality groups can be assessed by the nuclear magnetic resonance (NMR) method [99,100]. The method is based on emission and absorption by these substances of energy in the radio frequency range of the electromagnetic spectrum [101]. Molecules of each substance in the composition of a sample under study are determined as specific peaks, including those that characterize conformational changes in proteins, water mobility and other changes.

Magnetic resonance tomography (MRT) makes it possible to obtain spatial resolution of the composition of a sample and measure quantitatively parameters closely associated with meat properties, such as pH and water holding capacity, in each point of a NMR image [101].

Renou et al. [102] analyzed pork of different genotypes (halothane-positive and halothane-negative) applying the nuclear magnetic resonance method. The authors registered spin–spin relaxation time of water protons. The study demonstrated that the spin-spin interaction is closely related to a rate of a post-mortem decrease in pH and denaturation changes in proteins. Data obtained by Decanniere et al. [103] showed that using NMR imaging of porcine muscles it is possible to reveal animals that carry the halothane-positive gene, which allows differentiation of stress-sensitive pigs from normal animals.

Borowiak [104] identified NOR and PSE pork by the non-destructive and rapid method of pulsed nuclear magnetic resonance. According to the data of the author, quality of meat can be assessed by excitation of proton spin, which makes it possible to determine its properties, including technological characteristics and establish the character of autolysis. Investigations were carried out on the *longissimus dorsi* muscle of different genotypes of pigs. The spin-lattice and spin-spin relaxation times of water protons were determined. The authors established that the two-component relaxation behavior of spin lattice is closely linked with the rate of post-mortem drop in pH and protein denaturation. Based on the results obtained, it was shown that the differences in the pH value of muscle tissue were the largest two hours after animal slaughter. According to the results of the study, the authors classified meat with pH 6.3 as normal, with 6.0 <pH> 6.3 as meat with intermediate properties and meat with pH < 6.0 as PSE.

Taking into consideration that structural changes in animal muscles in the process of rigor mortis can be determined by the method of proton NMR relaxation, Miri et al. [105] and Bogner et al. [106] used this method to study meat from pigs that were sensitive and resistant to stress. As experiments showed, this method allows identification of pork with the normal course of autolysis with confidence of up to 85%. It was established that animals that were susceptible to the malignant hyperthermia syndrome give PSE meat.

Bogner et al. [106] investigated nuclear magnetic resonance (NMR) relaxation parameters of muscle tissue of normal pigs and pigs that were susceptible to malignant hyperthermia. It is known that the electronic envelope of the molecular responses to the external magnetic field and strives to shield it. The results of the relaxation measurement and multiexponential analysis of T2 curves showed a shift between different levels of water molecule protection upon action of NMR, which can predict an increased loss of water in muscle tissue after slaughter. The authors believe that using NMR it is possible to differentiate meat into one of three groups: normal, pale-soft-exudative, and dark-firm-dry.

Li et al. [107] in their study reported that it is possible to identify pork with different quality using NMR with low strength of magnetic field.

High performance in meat quality analysis was shown by the method of fluorescence spectroscopy, which is a variation of electromagnetic spectroscopy and analyzes fluorescence from a sample. This method is based on using a beam of light, as a rule ultraviolet light, which excites electrons in molecules of an analyzed sample and makes them emit light of lower energy. Amino acid tryptophan is a basis for the formation of fluorescent proteins with chromophores being in the anion state upon the physiological conditions. Interaction of tryptophan with the molecular environment of the cell is the most important factor influencing changes in spectra [14].

Fluorescence spectroscopy was proposed for the first time for quality analysis of meat and fish products based on their own fluorescence by Jensen et al. in 1986 [108]. According to the patent, a meat product, which quality is to be controlled, is subjected to an impact of electromagnetic radiation in a range of about 325–360 nm with the subsequent analysis of fluorescence that is typical for product biological components determining its quality. This analysis makes it possible to determine fluorescence that is characteristic of bones, cartilages, connective tissue and/or fat, as well as changes in pH and meat structure [14,109].

Despite availability and wide possibilities, the NMR method has not found application in meat science, apparently, due to the high cost of NMR spectrometers.

For rapid assessment of meat quality traits, a non-destructive method of hyperspectral imaging was proposed. This method combines a possibility of digital visualization and spectroscopy in a single system and is part of methods which are called spectral imaging or spectral analysis. The term "hyperspectral imaging" comes from the development of aerial photos by NASA (AIS) and AVIRIS in the middle of the 1980s. A hyperspectral image is a three-dimensional data array, which includes spatial information (2D) about an object supplemented with spectral information (1D) for each spatial coordinate. In other words, each point of an image corresponds to the spectrum obtained in this point [110].

The main advantage of the method consists in the fact that hyperspectral imaging collects and processes information from the entire electromagnetic spectrum emitted by an object [111]. Disadvantages include cost and complexity. Fast computers, sensitive detectors and big capacities for data storage are necessary for analysis of hyperspectral data.

The use of this method for meat quality assessment gained momentum at the beginning of the 21st century. Huang et al. [112] and Barbin et al. [113] obtained hyperspectral images of porcine m. *longissimus dorsi* of three quality groups (PSE, RFN and DFD) in near infrared range (from 900 to 1700 nm). Later Barbin et al. [113] observed reflectance differences between samples of three quality groups at wavelengths of 960, 1074, 1124, 1147, 1207 and 1341 nm. The data obtained indicate that pork groups can be reliably distinguished with the accuracy of up to 96 %. The researchers used the results of spectral information for prediction of color characteristics (L*a*b*), pH and drip losses. To predict these traits, certain wavelengths that were linked with each of them were chosen. It was established that values of lightness (L*), pH and drip losses can be predicted with the coefficients of correlation of 0.93, 0.87 and 0.83, respectively.

According to earlier results obtained by Qiao et al. [114], drip losses, pH and pork color can be predicted using hyperspectral imaging with coefficients of correlation of 0.77, 0.55 and 0.86, respectively. The authors suppose that this method can classify pork quality groups with regard to its exudative characteristics and color.

Therefore, it can be assumed that the hyperspectral imaging method is a potential tool for rapid identification of pork quality.

There have been attempts to use ultrasound for meat quality assessment. El Karam et al. [115] applied ultrasound to classify bovine muscles by scanning their acoustic parameters (velocity, attenuation and backscattering intensity). As investigations showed, the positive results of identification that correlated with the chemical composition of the samples were obtained in more than 80 % of analyses.

Conclusion

It is known from national and foreign publications that most often meat with non-traditional course of autolysis is revealed after animal slaughter by measuring, as a rule, pH, water binding capacity and drip losses, which requires preparation of samples (mincing) and certain time for analysis. The review presents non-invasive methods for identification of meat quality groups, which preferability consists in the fact that they allow objective, rapid and quite reliable qualitative and quantitative assessment of chemical, physical and physico-chemical characteristics of meat in real time without destruction of a sample. Taking into consideration the heterogeneity of the meat composition and structure, the specialists face the task of modernization of non-invasive methods and their adaptation to samples under study.

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