EXPERIMENTAL SYSTEM FOR ASSESSMENT OF FREEZING AND DEFROSTING PROCESSES OF MEAT

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Abstract. The development of an experimental system for monitoring the freezing and defrosting processes of meat will help optimize the freezing-defrosting regimes, particularly, in shock freezing. Non-destructive assessment of dynamic changes in the volumetric properties of meat tissue during freezing and defrosting is based on ultrasonic monitoring, using the velocity and attenuation of ultrasound, as well as changes in the spectrum and shape of the ultrasonic wave. Changes in ultrasonic parameters are specific to different water and fat contents in meat and allow us to determine it using temperature dependencies. The aim of the study was to track such dependencies in the temperature range from plus 25 to minus 30 degrees Celsius. Measurements were carried out on samples of lean and fatty pork with a fat content from 4% to 55%. Ultrasound propagation parameters were measured in the frequency range of 0.8 and 2 MHz. The samples were frozen using a REMS Frigo 2F-Zero electric tube freezer with temperature control using a calibrated thermocouple. The following trends were observed during the freezing stages. The ultrasound velocity decreased in lean meat and increased in fatty meat when cooling at temperatures above zero. The rapid drop in ultrasound signals at temperatures below zero is associated with the onset of the crystallization process and the presence of both liquid and crystalline components. The study showed that the dependences of ultrasound velocity and the intensity of ultrasound signals as an indicator of sound conductivity and their dependence on temperature can serve as indicators of the degree of freezing and thawing in the volume of meat at different fat and water contents.

Keywords: meat products, ultrasonic testing, fat and water content, shock freezing.

Introduction

Assessing the water and fat content in meat is essential for several reasons. Consumers are increasingly attentive to dietary fat content, making the fat percentage an important consideration in food selection [1]. Additionally, meat quality and taste are significantly influenced by chemical lean content, with intramuscular fat playing a pivotal role in defining various quality parameters [2]. Furthermore, the water-holding capacity (WHC) of meat substantially affects visual appeal, weight retention, cooking yield, and sensory attributes. Current literature indicates that WHC primarily depends on extra myofibrillar water, which resides outside the myofibrillar protein network [3]. Several techniques exist to measure fat and water levels in meat, including dual-energy x-ray absorptiometry (DXA), magnetic resonance imaging (MRI), optical coherence tomography, hyperspectral imaging, Raman spectroscopy, and thermal imaging. Studies have employed hydrostatic density measurements to investigate correlations between meat density and its content of water, fat, and proteins [4]. DXA effectively quantifies fat mass, lean mass, and bone mineral content, with predictive models based on DXA data providing highly accurate estimations of carcass composition, especially for lean and fat tissues. Recent advancements in imaging methods like DXA, computed tomography (CT), and MRI have significantly enhanced the evaluation capabilities of meat and carcass quality across various animal species, including pigs, sheep, and goats. Additionally, optical methods such as visible and infrared reflectance spectroscopy, hyperspectral imaging, and Raman spectroscopy have become increasingly relevant for monitoring meat quality [5; 6]. Ultrasound measurement techniques are another promising approach for assessing the water and fat composition of meat, offering advantages like portability, cost-effectiveness, and the ability to assess entire samples integrally. Currently, ultrasound is being used to study the physicochemical properties of meat and meat analogues, offering a non-destructive and real-time monitoring approach. In meat, ultrasonic techniques assess salt content, texture, and structural changes during processes like dry salting, while in plant-based analogues, they correlate with cutting force, moisture content, and extruder process control [7-9]. Ultrasonic wave velocity can indicate the relative proportions of protein, water, and fat in muscle tissues and it typically ranges between 1520 and 1660 $m \cdot s^{-1}$, depending on the composition [10]. However, because ultrasound velocity has a nearly linear correlation with water content (gradient of approximately 2.5-3.5 $m \cdot s^{-1}$ per 1% water content) and fat content similarly affects velocity, distinguishing water from fat using ultrasound alone remains challenging. Temperature variability further complicates measurements, as ultrasound velocity depends

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heavily on temperature for all meat tissue constituents individually and in combination [11]. Consequently, the objective of this study was to investigate meat samples with varying water and fat content across different temperature conditions. This work aims to create a robust ultrasonic-based model capable of precisely differentiating water and fat contents by employing multiple independent ultrasound parameters.

Materials and methods

Fresh pork meat specimens were prepared by cutting parallel slices from the meat (Figure 1). To evaluate hydration effects, measurements were conducted on both initial and hydrated specimens. Hydration was performed by uniformly injecting water into each sample using a syringe, adding water equivalent to 12% of the specimen's initial weight. Fat and lean meat proportions were estimated using specialized pattern recognition software programmed in C Sharp language. This software performed pixel analysis, categorizing pixels into fat or lean meat based on their proximity to defined classes in the RGB color space. Four selected samples exhibited varying fat contents: specifically, 4%, 22%, 45%, and 55%. Minced meat specimens were prepared from lean pork by grinding. These samples were then systematically varied to achieve different levels of fat content (4%, 22%, 45%, and 55%) and hydration. Three hydration levels non-hydrated and two levels of hydration were combined with fat content variations, resulting in a comprehensive experimental matrix.

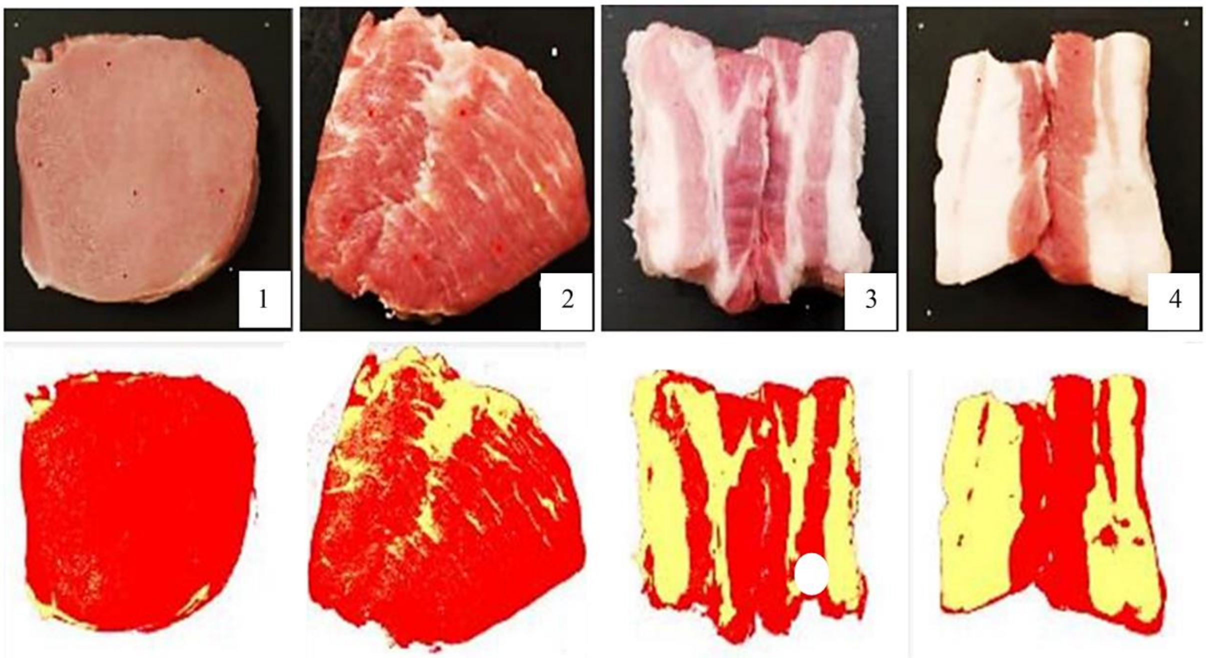

Fig. 1. **Meat specimens differing by fat content**: 1 – 4% fat content in meat specimen; 2 – 22% fat content in meat specimen; 3 – 45% fat content in meat specimen; 4 – 55% fat content in meat specimen; original photo and corresponding processed images with segmented lean meat and fat are presented in the top and bottom rows

Ultrasonic measurements of meat specimens were done in the through transmission mode using a pair of coaxial transducers with plane parallel surfaces. The transducers were stiffly arranged on a caliper-based device with consoles to provide smooth sliding of the acoustic base without a noticeable backlash and precise reading of the base (Figure 2 – 1, 2). To eliminate the error due to the base, it was rigidly fixed for specimens (55 mm) and minced meat (40 mm). Two ultrasonic frequencies were applied in a train of consequently recorded signals, at 0.8 and 2.0 MHz, coinciding with work frequencies of the transducers. The transducers were excited by short (2-period) tone-bursts at these frequencies under a sine envelope. The signals transmitted through the object were recorded using an experimental ultrasound device with a variable gain amplifier, a 10-bit analogue to digital conversion with a sampling frequency of 30 MHz and signals averaging rate 16. Ultrasonic measurements of meat specimens were done in the through transmission mode using a pair of coaxial transducers with plane parallel surfaces.

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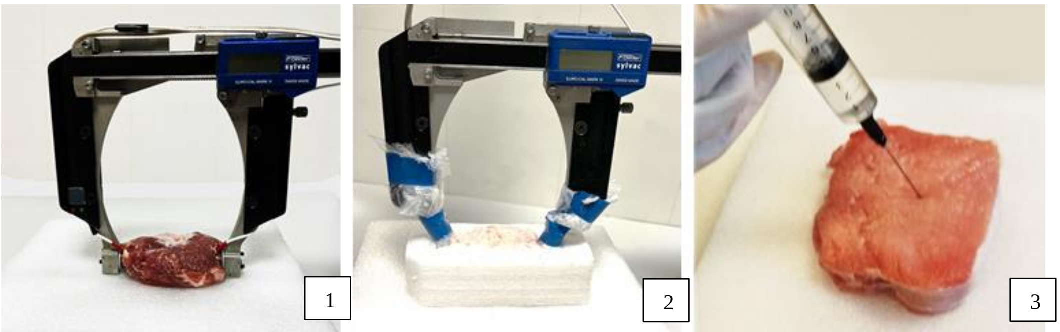

Fig. 2. **Illustrations of experiment:** 1 and 2 – ultrasonic measurement of meat and mince specimens using a caliper-based probe with a pair of ultrasonic transducers operating in through transmission mode; 3 - uniform injection of water into the meat sample using a syringe

Three parameters of ultrasound propagation were measured: 1) ultrasound velocity at a frequency of 2 MHz; 2) signal intensity at a frequency of 0.8 MHz as an integral of its amplitude in each time window; and 3) signal intensity at 2.0 MHz. The velocity was determined as the ratio of the acoustic base to the signal arrival time considering the transducers constant. Under other constant conditions, the signals' intensity can be a measure of sound conductance that is inversely proportional to attenuation. The measurements were repeated 4 times with renewed contact and then averaged. The average reproducibility error for ultrasound velocity was 1.5 $m \cdot s^{-1}$ at an average about 1550 $m \cdot s^{-1}$, and for the intensity about 10-15%. The measurements in meat specimens were done at three constant temperatures 7, 17, and 27 °C to follow dependencies of the parameters on the temperature and their temperature gradients. The temperature was controlled by a thermometer inserted inside the specimen and the allowable deviation was within ± 1 °C. In the case of mince, measurements could be carried out only at a temperature of 27 °C, because at lower temperatures, a radical decrease in the signals to the noise level was observed.

Results and discussion

The results demonstrated pronounced effects of fat, water and temperature factors on the measured ultrasonic parameters of meat as it was expected and coincided with reported data in some publications before [10; 11]. Our attempt was to illustrate its complex action and to represent data promoting the creation of more accurate descriptive and applied diagnostic models in the future. Figure 3 shows changes of ultrasound velocity in meat depending on its fat content and temperature for the initial and hydrated states. Initially, water content was within a typical value range of market sales, i.e. about 75%, and then increased by an additional 12% injection by weight reaching in total about 78%. In both states, the dependences of ultrasound velocity on the complex influence of fat content and temperature are the same. At a high temperature of 27 °C, the highest velocity values are observed in fat-free meat and gradually, although non-linearly, decrease as the fat content increases. At a low temperature of 7 °C, there is a contrary trend: the highest velocity is in the fatty specimen and nonlinearly decreases with a decrease of fat. At medium temperature 17 °C, these trends compensate for each other, and no prominent changes of the resulting velocity occur. The found effects are easily explained by the temperature dependence of ultrasound velocity in water that is the main volumetric component of muscle tissue, and its trend to increase linearly with temperature growth [12]. Conversely, fat softens with increasing temperature and ultrasound velocity in it decreases. Negative trends in ultrasound velocity for fat with temperature were noted for the majority of fat containing biological tissues [13].

Although an increase in water content does not lead to radical changes in the character of temperature dependence on meat, additional water leads to a regular decrease in the ultrasound velocity in samples with low fat content. An increase in water content by 2.5-3.0% reduces it by 8-10 $m \cdot s^{-1}$ that conforms to earlier findings [9]. Figure 4 presents the same results plotted in 3D coordinates to demonstrate that the combined 3D fat-temperature spatial distribution of the velocity can serve as a virtual model for potential application of pattern recognition methods for the tissue composition analysis. The model can be converted to the fat-water domain or even in 4D space including the temperature factor.

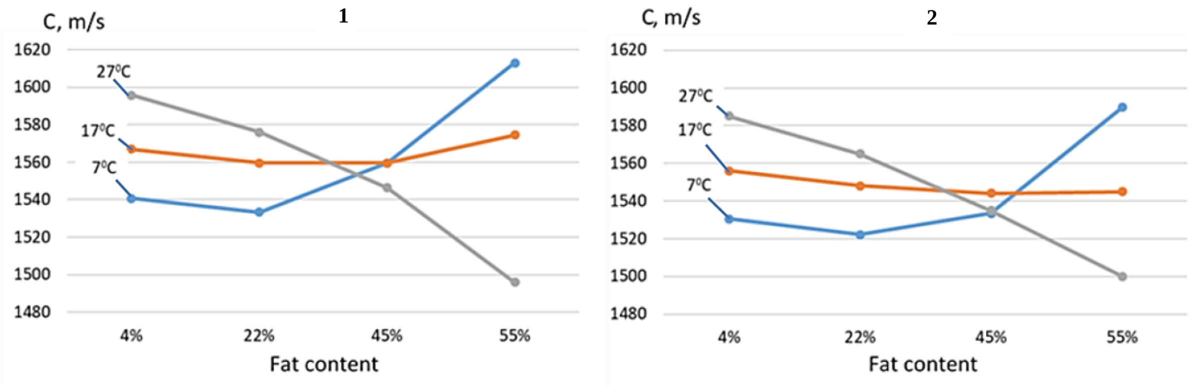

Fig. 3. **Dependence of ultrasound velocity C on fat content in meat at three temperatures obtained by measurements in meat specimens:** at initial (1) and hydrated (2) states

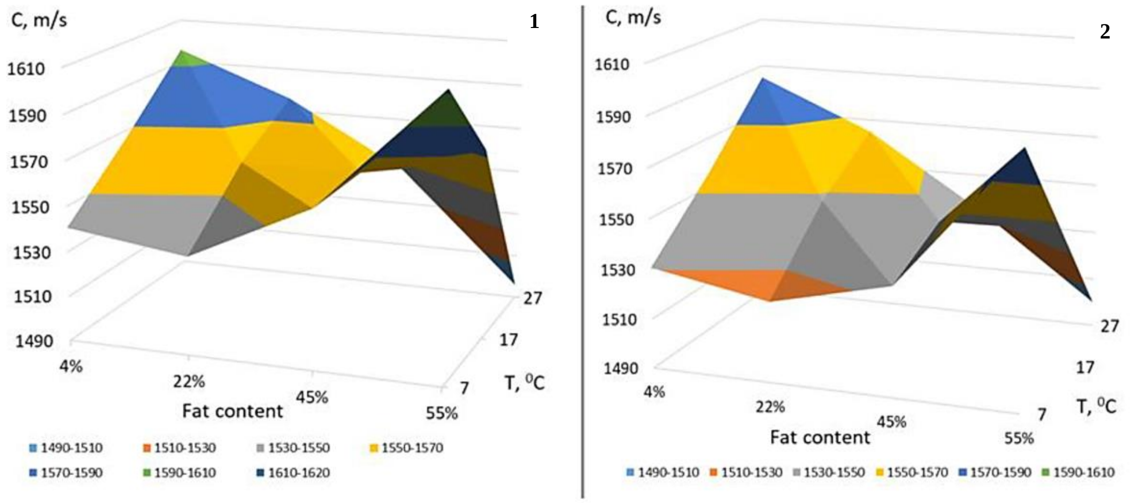

Fig. 4. **3D plots illustrating complex dependency of ultrasound velocity C on fat content and temperature in meat specimens:** at initial (1) and hydrated (2) states

The same dependences for another parameter of ultrasound propagation – signal intensity (analogous to the inversely proportional value of attenuation) was obtained (Figure 5).

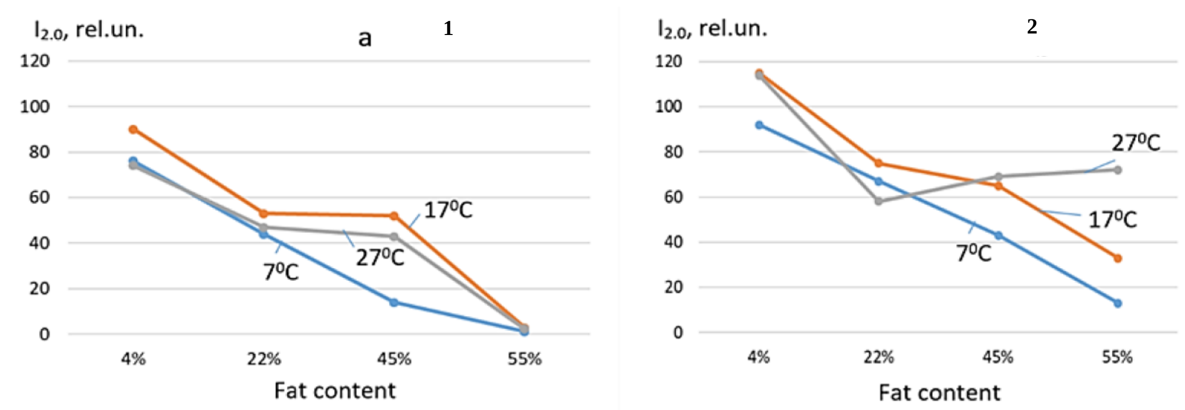

Fig. 5. **Dependence of ultrasonic signal intensity at 2.0 MHz I2.0 on fat content in meat at three temperatures obtained by measurements in meat specimens:** at initial (1) and hydrated (2) states

The character of these dependences differs the same for velocity. The general trend is a decrease in intensity as evidence of an increase in attenuation with increasing the fat content, and this appears over the entire temperature range. Increasing water content leads to an increase in signal intensity. On a relative scale, this effect is most pronounced for fatty specimens. Obviously, the presence of additional water is associated with better sound conductivity in all cases.

Another discovered independent parameter was the intensity ratio at 0.8 and 2.0 MHz, the 3D graphs for which are shown in Figure 6. The behavior of this parameter is remarkable in that its value and distribution pattern in the fat-temperature domain showed a strong influence of hydration (compare Figure 6.1 and 2) in fatty specimens. The sound conductivity at high frequencies there increased markedly with the addition of water.

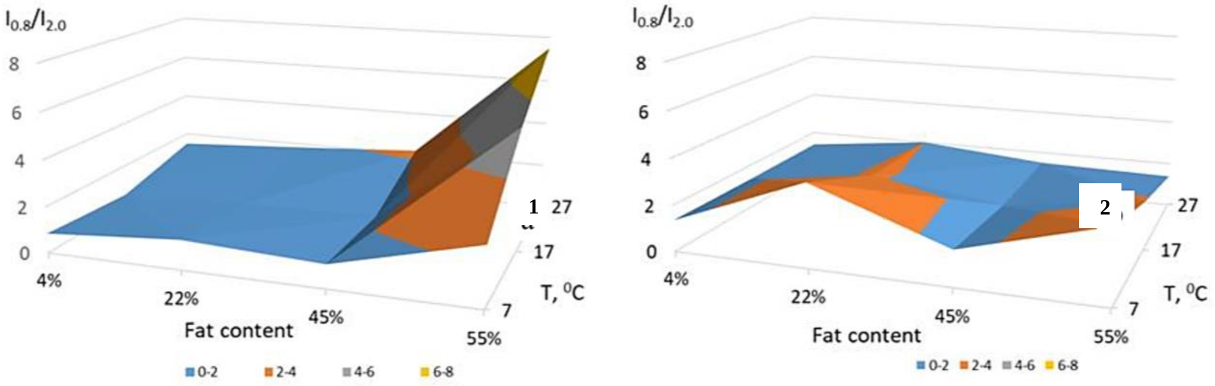

Fig. 6. **3D plots illustrate complex dependency of ratio of signal intensities at 0.8 and 2.0 MHz I0.8/I2.0 on fat content and temperature in meat specimens:** at initial (1) and hydrated (2) states

The results for two parameters for minced meat, ultrasound velocity and signal intensity at a frequency of 2 MHz at a temperature of 27 °C are shown in Figure 7. The graphs are built in fat-water coordinates and show smooth and directional changes according to the variation of these both factors.

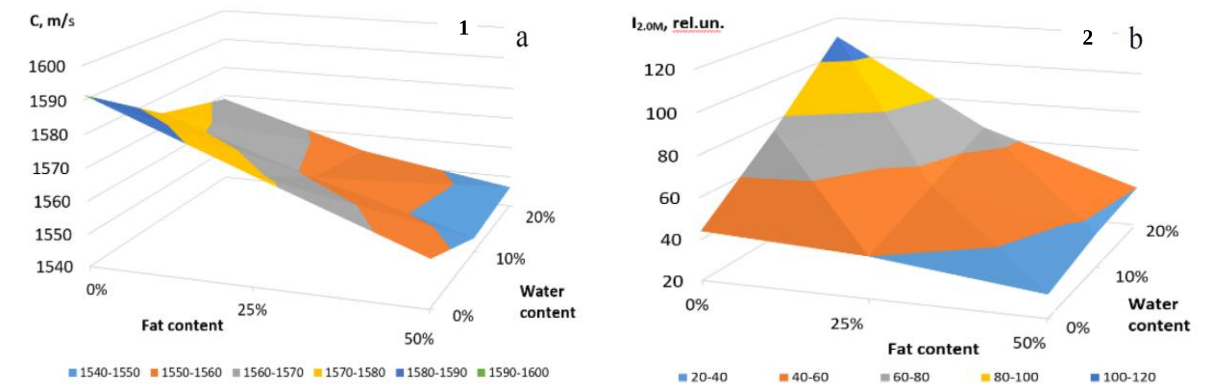

Fig. 7. **3D plots illustrating:** 1 – complex dependency of ultrasound velocity C; 2 – signal intensity at 2.0 MHz $I_{2.0}$ on fat and water contents for minced meat at 27 °C

The nature of the dependences for velocity and intensity differ significantly (compare Figure 7.1 and 2). In the case of the potential use of algorithms of pattern recognition, these models presented mathematically can serve as decision rules for determining water and fat. The intersection of the values of these parameters for a new object with an unknown content of fat and water can give their unambiguous definition. However, it should be noted that so far these data have been obtained at a fixed temperature.

Our experimental results demonstrate that ultrasound velocity in meat exhibits distinct temperature-dependent behavior during freezing: while velocity increases in high-fat samples (55% fat) during cooling above 0 °C, it decreases in lean meat (4% fat), with abrupt changes below 0 °C due to ice crystallization – a phenomenon not captured in prior room-temperature studies [11]. Unlike conventional single-parameter approaches, our method combines multi-frequency ultrasonic measurements (0.8/2.0 MHz ratios, velocity ranges of 1550-1730 $m \cdot s^{-1}$) and 3D modeling to differentiate fat/water content more accurately, particularly during phase transitions [12].

Conclusions

1. The results confirmed known variations in ultrasonic parameters depending on temperature, water content, and fat content, and also demonstrated the potential of using their complex interdependencies for differential assessment of meat composition. For example, the speed of ultrasound in fat-free meat at a temperature of 27 °C was about 1550 $m \cdot s^{-1}$, while an increase in fat content to 55% reduced the speed to 1520 $m \cdot s^{-1}$.
2. Changes in ultrasound speed and signal intensity – as indicators of sound conductivity (inverse of attenuation) – and their temperature dependencies can serve as criteria for evaluating fat and water content in meat. For instance, an increase in water content by 12% led to a decrease in ultrasound speed by 8-10 $m \cdot s^{-1}$ in samples with low fat content.
3. The application of artificial intelligence approaches, in particular pattern recognition algorithms, could be implemented in the future meat analysis based on a larger database.

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