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Review

Development Trend of Rapid and Non-Destructive Detection Technology for Intramuscular Fat Content in Large Livestock Such as Live Cattle

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Abstract

With the steady growth of the Chinese economy and the improvement in the living standards of residents, consumption of meat from cattle, sheep, and pigs continues to increase, and demand for high-quality meat is growing stronger. Intramuscular fat (IMF) content is a key indicator of meat quality, directly affecting the flavor, juiciness, and overall palatability. Therefore, the development of rapid, non-destructive testing technologies is crucial for optimizing feeding management, improving meat quality, and enhancing market competitiveness. This article reviews research progress on emerging technologies, including B-mode ultrasound, near-infrared spectroscopy, Raman spectroscopy, hyperspectral imaging, terahertz imaging, electrical impedance imaging, and nuclear magnetic resonance imaging (MRI), for detecting IMF content in live cattle, sheep, and pigs. This study aimed to provide theoretical references and technical guidance for the development of rapid, non-destructive testing technologies in this field.

Keywords: intramuscular fat; non-destructive testing; living thing; B-mode ultrasonography; spectrum

1. Introduction

With the steady growth of the Chinese economy and the continuous improvement of rising household incomes, the consumption of beef, mutton, and pork has grown steadily upward trend, reflecting strong market demand for high-quality beef cattle and other large livestock. According to data from the Food and Agriculture Organization of the United Nations (FAO), global demand for meat has risen steadily over the past decade. The FAO Meat Price Index has shown a generally upward trend during this period, reflecting strong market expansion and increasingly tight supply–demand conditions [1,2]. The quality of meat from cattle and other large livestock is a key factor in market competitiveness, and it is largely determined by the content of intramuscular fat (IMF), which directly influences meat flavor, juiciness, and tenderness. Furthermore, IMF content enhances both the sensory quality and nutritional value of meat. Based on insights from the existing literature on the upgrading trend of beef consumption, combined with general industry expectations regarding demand for high-end products, it is projected that by around 2030, the supply–demand gap for high-end beef with an IMF content ≥8% in China could reach 1.7 million tonnes [3]. Concurrently, there is a growing structural deficit for premium meat from other large livestock, driven by the rising consumer demand for high-quality protein, primarily limited to specific pig breeds such as Black or Spotted pigs, as other species lack the genetic predisposition to achieve this fat content level. Given these substantial and structurally constrained gaps, demand for such high-quality meat is expected to continue its strong upward trajectory. Most non-destructive techniques for assessment are based on detecting IMF content in animal carcasses, rather than live animals. However, *in vivo* determination of IMF content in living organisms is particularly important for breeding and evaluating the quality of slaughter. At present, many enterprises and research directions mainly rely on post-slaughter determination rather than *in vivo* IMF measurement [4]. During *in vivo* measurement, factors such as animal respiration, movement, and hair cover introduce and often prevent the results from meeting the commercial grading requirement of ≤5% error. At present, the technologies used for rapid non-destructive testing of IMF in live cattle and other large livestock mainly cover the following categories, but there are significant differences in the development and application stages of these technologies. In the livestock breeding industry, such as cattle and other large livestock, the breeding cycle is longer compared to other animals. Non-destructive testing technology can provide critical tools for the breeding of these

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livestock. By enabling early insight into an animal's internal composition, these technologies can provide a scientific basis for breeding decisions, facilitate the selection of superior breeding stock, and support final quality grading prior to slaughter.

B-mode ultrasound (B-mode US) scanning technology is currently the most widely used and commercialized technology in practical applications. It uses high-frequency acoustic imaging to indirectly estimate IMF content by analyzing image features (e.g., grayscale, texture) of specific areas like the longissimus dorsi muscle (eye muscle), sometimes in combination with sound velocity measurements. Specialized portable veterinary ultrasound devices, such as those used to measure backfat and eye muscle area, have been used in field settings. Its advantages include real-time operation, portability, and relatively low cost. However, its core limitation lies in the limited direct quantitative accuracy of deep IMF content, which is susceptible to operator skill, animal activity, and tissue interference. The targeted determination of high-precision *in vivo* IMF content still relies on statistical or machine learning model assistance, and is a research hotspot for continuous optimization and validation. The application of near-infrared spectroscopy technology *in vivo* faces significant challenges. It aims to establish a quantitative measurement model for IMF content using organic matter characteristic absorption spectra. Reflective methods have been widely used and available models in carcass detection [5], but *in vivo* applications are limited by the strong scattering/absorption of skin, hair, and subcutaneous fat, resulting in low practicality for shaving measurements. There is currently no mature commercial equipment specifically designed for live use. The research on transmission and the use of "second window" (1000–1700 nm) light aims to improve penetration depth, which is currently a frontier hotspot and is in the stage of laboratory exploration and prototype verification. Establishing a robust *in vivo* calibration model is its core challenge. Hyperspectral/multispectral imaging technology is mainly used for grading marbling patterns (visualized by IMF) on the cut surface or carcass. The grading criteria are shown in Fig. 1. Its advantage lies in combining spatial and spectral information, enabling visualization and large-area scanning. However, the application of live detection is limited by the burden of massive data processing, animal motion artifacts, hair/skin interference, and difficulties in obtaining deep tissue information [6]. It is still in the stage of laboratory principle verification and algorithm research, and practical live detection still needs breakthroughs. Other emerging technologies, such as Raman spectroscopy, terahertz imaging, electrical impedance imaging, magnetic resonance imaging (MRI), and computed tomography (CT), are mostly in the early stages of basic research or laboratory validation, and have problems such as high prices, low imaging resolution, and large equipment size. Raman spectroscopy has strong specificity but weak signal and is severely affected by *in vivo* fluorescence interference [7]; Terahertz imaging is sensitive to water and its penetration depth and system cost are bottlenecks; Electrical impedance imaging has low cost but limited resolution, and *in vivo* prediction models need to be further validated; MRI has high accuracy, but the equipment is extremely expensive, bulky, and the scanning time is long. It is an exploratory research direction as it is far from practical directional measurement and detection of IMF content *in vivo*.

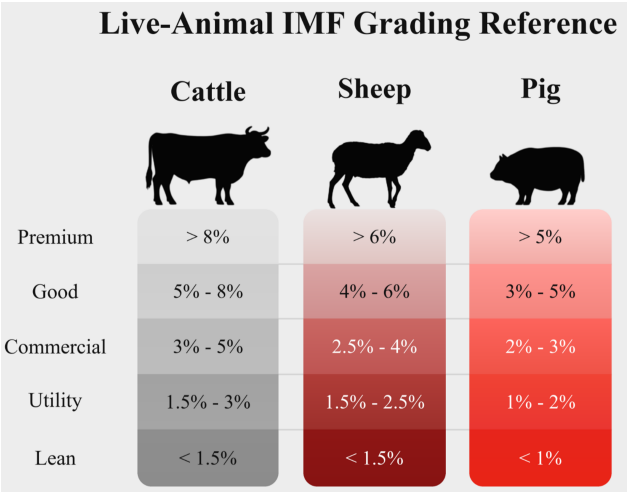


Fig. 1. Meat zoning and quality standards. This table presents general meat quality classifications for cattle, sheep, and pigs based on intramuscular fat (IMF) content. The grading levels (Premium, Good, Commercial, Utility, and Lean) summarize the approximate IMF thresholds commonly associated with high-quality meat across different international grading systems. Specifically, the Premium category corresponds to the high-grade standards sought by the market (e.g., cattle >8%, sheep >6%, and pigs >5%).

At present, traditional detection methods have problems such as strong destructiveness, long detection time, and inability to achieve rapid and large-scale detection [8]. The existing methods for rapid non-destructive testing include B-mode US. In addition to the mature *in vivo* application foundation of ultrasound technology, other technologies have significant technical bottlenecks in the precise, rapid, and universal quantitative detection of IMF content *in vivo*. It is urgent to conduct in-depth research to overcome the accuracy, speed, and cost challenges brought by the complexity of the living environment. At the same time, with the development of artificial intelligence, it has been found that the combination of multiple technologies and artificial intelligence will be better applied in the rapid non-destructive detection technology of IMF in live cattle and other large livestock. Currently, the identification of IMF in meat is constrained by a fragmented standardization landscape. Unified technical guidelines are absent, and cross-species applicability remains unvalidated. Although vari-

ous countries have established grading systems, the corresponding technical implementation pathways are markedly inconsistent. Algorithmic development, while rapid, has significantly outpaced the formulation of relevant standards [9,10,11]. Moreover, there is a systemic lack of evaluation criteria and industry consensus regarding core performance metrics—such as speed, cost, and accuracy—as well as the mathematical models underpinning critical technologies (e.g., motion artifact removal and suppression of optical interference from hair), which have yet to be publicly disclosed.

This article reviews the current application status and development trends of rapid non-destructive testing technology for IMF in live cattle and other large livestock. It mainly focuses on in-depth analysis of this technology in the past 20 years, exploring how it can help improve the quality of domestic cattle and other large livestock, enhance market competitiveness, meet consumer needs, and promote industrial technological progress. By analyzing the working principles, advantages, limitations, and practical applications of various technologies, we will also discuss the recent progress, challenges, and future prospects of accelerating and rapid non-destructive testing of IMF in live cattle and other large livestock. This review aims to provide a theoretical basis and technical guidance for rapid non-destructive testing of IMF in live cattle and other large livestock.

2. The Current Development Status of Rapid Non-Destructive Testing Technology

2.1 Acoustic Technology

Common acoustic devices such as B-mode ultrasound use high-frequency sound waves above the range of human hearing for detection. The technical principle is shown in Fig. 2 [12]. The B-mode US probe emits and receives high-frequency sound waves into the body, and uses the differences in echo intensity and time of different tissues to reconstruct a two-dimensional grayscale image in real-time through a computer. Representative images are shown in Fig. 3. Key advantages of B-mode US include relatively low cost, ease of operation, and its non-invasive nature [13]. It utilizes the principle of different wave velocities of ultrasound in various media [14]. Therefore, it can be applied in non-destructive testing for real-time monitoring of animals. However, the resolution of this technology is limited and may not be sufficient to provide very fine tissue details. Image quality can be compromised by noise and artifacts, meaning accurate IMF quantification cannot rely on ultrasound imaging alone. In order to achieve more effective non-destructive testing, many scholars have conducted relevant research and combined it with machine learning technology to further improve the accuracy of B-mode US for fat content determination [15].

This technology has gained recognition from numerous scientists for its reliability and deep penetration. However, there is still a need for a unified judgment standard when applying this technology to non-destructive testing of IMF in cattle and other large livestock. Currently, through extensive reading of domestic and foreign literature, it has been found that most measurements rely on a single value for judgment. Some authors have conducted standard analysis by empirically converting root mean square error (RMSE) and mean absolute percentage error (MAPE) [16,17,18,19,20,21].

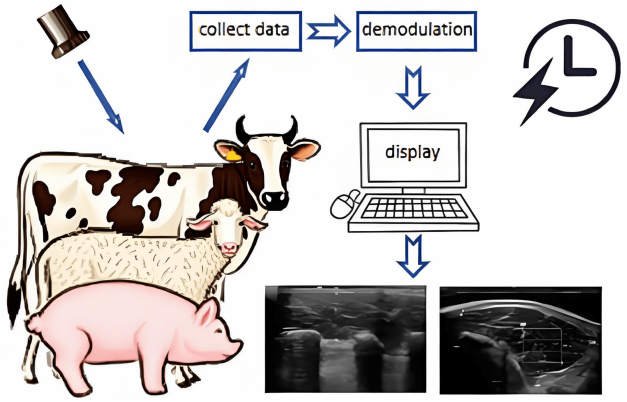


Fig. 2. Simple principle of B-mode US. The B-mode US probe emits and receives high-frequency sound waves into the body, and uses the differences in echo intensity and time of different tissues to reconstruct a two-dimensional grayscale image in real-time through a computer. B-mode US, B-mode ultrasound.

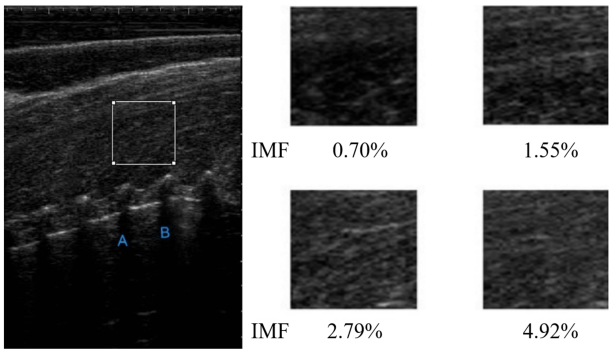


Fig. 3. Some common B-mode US images of IMF content.

Although one-sidedness in judgment is a drawback, it does not hinder the confirmation of the effectiveness and feasibility of ultrasound technology in predicting IMF content in live animals. However, the high-precision products available on the market today are mostly used in the veterinary field, and they are expensive. There are specific requirements for the hair on the detection site during testing, and trimming the hair will delay time and increase costs. Therefore, mathematical models are urgently needed; however, almost all current technologies still rely on contact ultrasound equipment for non-destructive testing. It is necessary to keep the tested object calm and reduce the hair on the tested surface. If we want to further improve speed and

efficiency, we can develop non-contact B-mode US. The development of ultrasonic technology will take longer than that of contact-based technology, and further improvement in accuracy can be achieved by combining sound and light technology [22]. However, the application of this technology in industry and animal husbandry has barriers, but it also provides a new idea for non-destructive testing of IMF in live cattle and other large livestock.

2.2 Optical Technology

Optical and acoustic devices differ greatly in principle and application, with the core being the significant differences in spectral distribution, energy levels, and information dimensions. Acoustics uses mechanical waves as a medium, while optics uses electromagnetic waves as a medium, with frequency bands spanning visible, infrared, ultraviolet, and even terahertz. Different bands correspond to different molecular transitions, lattice vibrations, and electronic states, which determine the exclusive design of detectors, light sources, spectral elements, and algorithms.

2.2.1 Optical Coherence Tomography Technology

Optical coherence tomography (OCT) has become a rapidly developing and promising new type of tomographic imaging technology in recent years. It was first proposed by Huang et al. [23] and is an imaging technology based on the principle of low coherence interference [24]. High-resolution microscopic structural images of the sample interior are reconstructed by emitting low-coherence light and precisely measuring the interference signal produced between the reference light and the light reflected from the sample's internal layers, as shown in Fig. 4. It does not require labeling, does not emit ionizing radiation, and is extremely sensitive to differences in tissue scattering. Therefore, it can clearly distinguish the microstructure of fat droplets from muscle fibers. Although the application of this technology is for non-destructive testing of IMF in live cattle and other large livestock. needs to be developed, it has been confirmed by scientists such as Thampi et al. [25] that this technology has the ability. To achieve fully automated, contactless, and nondestructive inspection with real-time results, and classify the quality of complete meat samples. The characteristics of a value of 0.94 and an average absolute error of 1.09 IMF% suggest that this technology has advantages over other technologies in prediction accuracy [25] and is a promising tool for predicting meat quality.

2.2.2 Near-Infrared Spectroscopy Technology

Near-infrared spectroscopy technology (NIRS) is one of the most widely used techniques in optical equipment. Near-infrared light is an electromagnetic wave between visible light and mid-infrared light. The American Society for Testing and Materials defines the spectral region with a wavelength of 780–2526 nm as the near-infrared spectral region. NIRS mainly applies two types of sampling techniques: transmission spectroscopy technology and reflection spectroscopy technology [26,27]. The working principle is shown in Fig. 5. However, this technology requires an expensive and time-consuming process to establish a calibration model. By applying near-infrared light from the second window (1000–1700 nm) and improving the compatibility between the technical solution and the device, near-infrared harmonic technology can be better applied to *in vivo* detection [28]. N. Barlocco and other scientists [5] have validated the feasibility of using penetrating NIRS for *in vivo* IMF measurement.

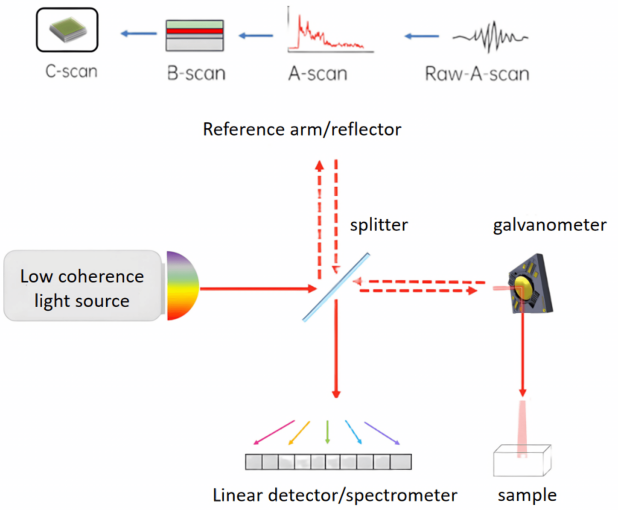


Fig. 4. Schematic diagram of the hardware structure of OCT technology. OCT, Optical Coherence Tomography.

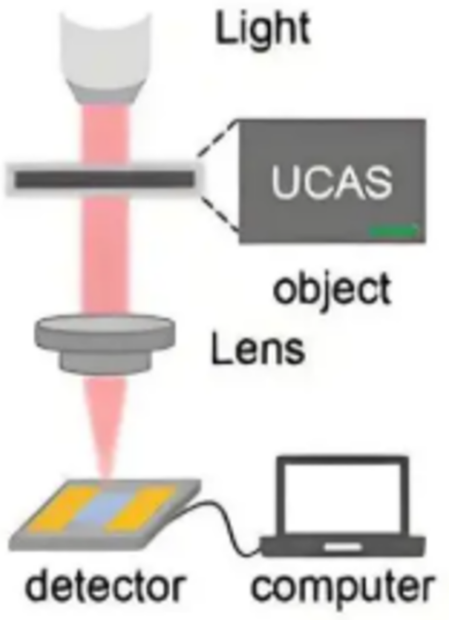


Fig. 5. Near-infrared (NIR) spectroscopy principle; near-infrared analytical system (NIRAS).

At present, the integration of this technology with machine vision is facing problems such as the inability to integrate into universal large-scale datasets, inadequate algorithms and models, which limit the improvement of machine learning and deep learning models in generalization ability before the formation of universal large-scale datasets [29]. However, this does not hinder scientists' preference for NIRS near-infrared spectroscopy, which is still a highly supported technology, but its application in detecting respiratory amplitude and complex environmental spectral noise in living organisms is a significant obstacle [4,30,31,32,33].

2.2.3 Raman Spectroscopy Detection Technology

Raman spectroscopy technology has been integrated with other technologies to develop techniques such as stimulated Raman, resonance Raman, micro confocal Raman, and surface enhanced Raman [34]. Raman spectroscopy technology has the advantages of rapid analysis and no need for sample preparation.

With the development of spectroscopic instruments, laser technology, and the improvement of information processing technology, the resolution and sensitivity of Raman spectroscopy have been greatly improved. In previous years, scientists have also proposed that Raman spectroscopy can be well used for fat identification [35]. Moreover, the molecular structure of oil substances can cause strong Raman effects, so Raman spectroscopy also has certain advantages in oil detection [36]. Scientists such as Robert et al. [37] used wide area Raman spectroscopy technology and cluster independent soft mode method, combined with multiple scattering correction, spectrometer noise reduction, and wavelength calibration noise reduction technology to establish models for animals such as pigs, cows, and sheep, which can detect the lipid composition of animal meat in a short time. This further confirms the feasibility of Raman spectroscopy non-destructive testing technology for fat detection courses. However, the operating environment for non-destructive testing of IMF in live cattle and other large livestock is not in the laboratory. China has made important breakthroughs in Raman spectroscopy detection technology and equipment in visible light or near-infrared bands, but there is still little progress in ultraviolet (UV) Raman spectroscopy detection technology suitable for outdoor natural environments [38]. Linear scanning confocal Raman spectroscopy has emerged as one of the rapidly advancing techniques in China in recent years. By integrating machine learning algorithms—such as support vector machines (SVM) and linear discriminant analysis (LDA)—researchers have achieved comprehensive and rapid characterization of the full spectrum of biochemical components within cells [39].

Raman spectroscopy technology is mainly in the laboratory research and preliminary application stage in IMF detection. Although various Raman spectroscopy techniques have been used for the detection of adipose tissue, their application in non-destructive testing of IMF still faces some technical challenges, such as low signal intensity and fluorescence interference [40]. These disadvantages can be complemented by combining with other techniques [41].

2.2.4 Hyperspectral Imaging Technology

Hyperspectral imaging technology (HSI) is an advanced imaging data technology that combines imaging and spectroscopic techniques. It can detect the two-dimensional geometric space and one-dimensional spectral information of the measured target by obtaining data in many narrow bands, and collect continuous and narrow band image information with hyperspectral resolution [42,43]. This technology is based on the radiation principle of matter, using the radiation signal emitted by matter itself due to its certain temperature to work. By analyzing specific wavelength parameters of a substance's reflection or radiation, the "spectral distribution" of the substance can be plotted. Due to the different reflection or radiation abilities of different substances, each substance has unique spectral characteristics that can distinguish it from other substances [44]. This technology is very similar to the near-infrared spectroscopy mentioned above, and can also be divided into reflective and projection methods. The two technologies can be combined to form a visible near-infrared HSI for the detection of animal carcasses [19].

However, as an emerging technology, HSI still faces a series of problems, such as large data volume, high real-time requirements, complex algorithms, and high costs. These issues limit its application in a wider range of fields, especially in rapid non-destructive testing of IMF in live cattle and other large livestock [45]. To overcome these challenges, researchers are exploring more efficient data processing algorithms and more economical imaging equipment. For example, by using a 128 × 128 array FP cavity tunable infrared wave disruptor based on micro-electromechanical systems (MEMS) technology, the flexibility and cost-effectiveness of hyperspectral imaging devices can be improved [44].

At present, this technology is widely applied to animal carcasses. Jun Qiao and other scientists [46] have successfully classified the marble patterns of 40 sliced carcass samples through HSI. Although HSI is still in the exploratory stage in the field of rapid non-destructive detection of IMF in live cattle and other large livestock, it has shown great potential for application with its hyperspectral resolution and unique substance recognition ability With the continuous optimization of data processing algorithms and the reduction of imaging equipment costs, HSI is expected to break through current technological bottlenecks and achieve a leap from laboratory to practical applications. This will not only provide an efficient and accurate detection method for animal husbandry but also promote the development of the entire industry towards intelligence and refinement.

2.2.5 Computerized Tomography Technology

CT uses X-ray tubes and detectors to measure the rotation of living organisms, continuously acquiring projection data at different angles, and generating cross-sectional grayscale images through computer reconstruction algorithms. Currently, in medicine, it is possible to measure the area/density of thigh or paraspinal muscle fat, which is highly consistent with autopsy results [47]. This demonstrates the feasibility of non-destructive testing *in vivo*, but the accuracy is still limited. Foreign researcher some scholars used machine learning methods to assist micro CT technology in successfully reconstructing 3D images of fiber materials [48]. The phenomenon of images indicates that CT technology is highly compatible with artificial intelligence and can be improved through deep learning-based technology [49]. Although the cost of CT technology is relatively low, the X-rays used have the problem of ionizing radiation. The purpose of using advanced technology today is to improve the taste and quality of food. Studies have shown that X-ray radiation hydrolyzes water to produce free radicals, accelerates fat oxidation, and produces aldehydes and ketones odor [50,51]. At the same time, high-dose or synergistic oxidation environments can reduce water retention, increase shear force, cause meat to become hard, or produce "irradiation odor" [52]. The radiation measurement of X-rays used for *in vivo* detection is relative to that used for food sterilization and irradiation. The radiation dose is relatively small, but there are other risks associated with long-term and multiple examinations in live testing, which can lead to losses for users. This risk can be avoided by reducing the number of tests or by using other spectral tests, such as near-infrared spectral detection reconstruction algorithms for non-destructive testing to eliminate radiation. However, this idea poses a challenge to spectral technology, but this technology still has great feasibility for rapid non-destructive testing of IMF in live cattle and other large livestock. According to existing literature, the application research of CT technology in direct detection of IMF in live large farm animals (cattle, sheep, pigs) is very limited. The main reason is that the radiation exposure risk, high cost, and operational complexity of CT limit its routine use in live agricultural animals. At present, relevant research mainly focuses on the following two categories: experimental small-scale *in vivo* studies (mainly on pigs), and medical/veterinary model indirect related studies [7]. The potential of CT in predicting live pig composition (including fat distribution) was discussed with high accuracy. However, it was emphasized that radiation dose, cost, and time cost are the main obstacles to its routine application on farms.

However, there is currently a lack of mature CT research specifically targeting IMF detection in live cattle and other large livestock. There are no large-scale, systematic agricultural research reports or commercial practices on the precise quantification of IMF content in live cattle and other large livestock using CT. The fundamental reason for this still requires interdisciplinary progress and development in order to better apply CT technology to non-destructive testing of IMF as soon as possible.

2.3 Electrical Technology

Electrical impedance tomography (EIT) is a new image reconstruction technique developed in recent years. It uses reconstruction algorithms to obtain cross-sectional images of electrical impedance based on the differences in conductivity parameters of different tissues within the organism, using injected alternating current signals and measured voltage data [53]. This technology is characterized by non-invasive, harmless, fast, inexpensive, easy to operate, and rich functions [54], but its imaging resolution is lower compared to traditional imaging techniques such as CT and MRI, which limits its accuracy and reliability in application [55].

In addition, EIT technology has impedance at the contact position between the electrode and the skin surface during measurement. Compared with the voltage drop of the internal impedance, the voltage drop on the contact impedance is quite large, and its value changes with different surfaces of the electrode position, which may cause significant errors in the system [56]. Not only are there errors in the skin during measurement, but the size and fat content of the measured body can also affect the construction of EIT ventilation images [57].

Currently, foreign scientists Afonso et al. [58] have demonstrated a significant correlation between bioelectrical impedance analysis (BIA) parameters (such as resistance Rs, reactance Xc, and impedance Z) and IMF content using another technique based on the principle of electrical impedance, BIA. He has also established a prediction model based on BIA parameters, further demonstrating the effectiveness of the BIA principle in predicting IMF content.

Although contact impedance and fat content interfere with EIT measurement results, this interference can be strategically harnessed in IMF detection. By analyzing the error data in the measurement, the fat content can be calculated in reverse, thereby transforming the original defect into a powerful means of detecting fat.

2.4 Magnetic Technology

Nuclear magnetic resonance (NMR) imaging technology is a spectroscopic analysis method based on nuclear magnetism, mainly utilizing the energy level splitting phenomenon of magnetic atomic nuclei (such as ^{1}H, ^{13}C, ^{11}P, etc.) in an external magnetic field. Low-field NMR is commonly used in non-destructive testing of IMF in live cattle and other large livestock [59]. Low field NMR is characterized by fast and non-destructive analysis of physical properties of samples, such as water and lipid status [60,61,62]. At present, scientist Ballerini [63] has demonstrated the feasibility of using MRI to determine the fat content in beef,

Table 1. Technical summary.

Technology	Current accuracy (Live IMF)	Speed	Cost	Technology maturity (Live Application)	Main advantages	Main challenges and limitations
B-mode US	Medium	Fast	Medium-Low	Applied cases available	Real-time, portable, easy to operate, low cost, good penetration	Limited quantitative accuracy for deep IMF; greatly affected by operator, animal movement, tissue heterogeneity; requires contact, hair treatment
NIRS	Reflectance: Low-Medium	Fast-Very Fast	Medium	Carcass mature; live research ongoing	Fast, non-contact potential, multi-component analysis potential	Live body: strong interference from skin/ hair/subcutaneous fat; robust calibration model difficult to establish; limited transmission depth
HSI	High (carcass)	Medium-Slow	High	Carcass research; live exploration	Visualizes spatial distribution (marbling); non-contact potential	Live body: large data volume, slow processing; severe motion artifacts; hair/ skin interference; difficulty in obtaining deep information; high cost
Raman	Laboratory stage	Medium	Medium-High	Basic research	High specificity, molecular fingerprint information, non-contact potential, minimal sample preparation	Live body: weak signal; severe fluorescence background interference; shallow penetration depth; complex equipment
EIT/BIA	Low-Medium (exploration)	Fast	Low	Exploratory research	No radiation, fast, portable, low cost, easy to operate	Live body: low resolution; contact impedance affects; insufficient model validation; tissue heterogeneity impact
CT	High	Slow	High (high for livestock use)	Medicine/veterinary; agricultural research limited	High resolution, provides 3D structural information, and accurate quantification	Live body: ionizing radiation risk; large, expensive equipment; long scanning time; animal sedation; ethical concerns
MRI	Very High	Slow	Very High (higher than CT)	Research validation	No ionizing radiation, extremely high soft tissue contrast, multi-parameter quantification potential	Live body: extremely expensive, bulky equipment; long scanning time; loud noise startles animals; motion artifacts

B-mode US, B-mode ultrasound; NIRS, near-infrared spectroscopy technology; HSI, hyperspectral imaging technology; EIT, electrical impedance tomography; BIA, bioelectrical impedance analysis; CT, computed tomography; MRI, magnetic resonance imaging.

demonstrating the feasibility of this technology in detecting IMF. However, further research is needed to apply this technology to live IMF. The main difficulty of the research lies in the high cost, long detection time, and high noise during the scanning process of MRI technology, which can easily startle livestock. The motion of the object being measured during the detection process may affect the quality of the image, but the resolution of this technology is higher compared to other technologies during normal use. In terms of artificial intelligence, it can be better integrated with the combination of artificial intelligence.

Compared to NMR imaging technology, non-destructive testing of live cattle and other large livestock still needs to overcome its high cost and image clarity issues. However, with the continuous advancement of superconducting materials, electronic technology, and manufacturing processes, the manufacturing cost of core components such as superconducting magnets and radio frequency systems of NMR instruments may gradually decrease. So, the application of rapid non-destructive testing of IMF in live cattle and other large livestock is just around the corner.

3. Prospect

In the future, the development of rapid non-destructive testing technology for IMF in live cattle and other large livestock will be driven by various factors. With the continuous increase in demand for high-quality meat, especially for meat with high IMF content, the accuracy, speed, and cost control of detection technology will become the focus of research. As shown in Table 1, technological integration is a key direction for future development, and multiple non-destructive testing technologies will complement each other to overcome the limitations of a single technology. For example, the combination of optical technology and acoustic technology can utilize the high sensitivity of optical technology and the deep penetration ability of acoustic technology to more accurately detect IMF content. In addition, with the continuous advancement of artificial intelligence technology, the optimization of algorithms and data processing capabilities will also be significantly improved. This will enable detection technology to more effectively handle complex living environments, reduce errors, and improve the reliability and consistency of detection results. At the same time, innovation in hardware technology and cost reduction will further promote the commercialization and popularization of these technologies. In the future, we are expected to see more efficient, accurate, and cost-effective non-destructive testing technology for live muscle fat applied in animal husbandry, thereby achieving precise feeding and quality grading, meeting market demand, and promoting the high-quality development of the entire meat industry.

4. Conclusions

The rapid, non-destructive detection of IMF in live cattle and other large livestock is at a pivotal stage, moving from foundational research toward practical implementation. Currently, B-mode ultrasound is the only technology that has achieved limited commercial adoption for live-animal assessment. While other advanced modalities, such as near-infrared spectroscopy, hyperspectral imaging, Raman spectroscopy, MRI, and CT, have demonstrated considerable potential in carcass evaluation or controlled environments, their application *in vivo* remains largely exploratory or in the validation phase.

The barriers to widespread adoption are complex and multifaceted. Key technical challenges include motion artifacts, respiratory interference, and optical disruptions caused by hair and skin. In addition, high equipment costs and the lack of robust, generalizable prediction models present significant hurdles to real-world application.

Despite these obstacles, strong and growing market demand for high-quality meat, highlighted by a projected shortfall of 1.7 million tonnes of high-end beef in China by 2030, provides powerful momentum for continued innovation. Overcoming current technological bottlenecks is not merely an academic pursuit; it is essential to enabling precision breeding programs, supporting objective pre-slaughter quality grading, and ensuring a sustainable, high-quality meat supply chain. Future progress will depend on coordinated efforts in technology convergence, algorithmic refinement, and the establishment of unified industry standards.

Author Contributions

Authors HG, LL, and YL designed the research study. Authors HG and XC provided guidance and advice. Author LL conducted the research (investigation). Authors CL, ZY, and XZ analyzed the data (validation/software). Authors CL, TC, and LL drafted the manuscript. XC and TC contributed substantially to the study design, data acquisition, and data analysis and interpretation. All authors contributed to the critical revision of the manuscript for important intellectual content. Furthermore, all authors have contributed sufficiently to the work and have agreed to be accountable for all aspects of the research. All authors have read and approved the final manuscript.

Ethics Approval and Consent to Participate

Not applicable.

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Conflicts of Interest

The authors declare no conflicts of interest.

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