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Meat Product Adulteration: Modern Detection Methods and Food Safety Assurance

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Abstract
Intentional adulteration of meat products through falsification can impact product safety and consumer properties. Adulteration involves the addition of low-quality or unauthorized ingredients and deviations from declared standards, posing potential health risks to consumers. Various laboratory methods, including DNA analysis, chemical, and physicochemical studies, are used to control adulteration. These methods allow for precise determination of product composition and identification of discrepancies with declared characteristics. However, there is no universal method capable of detecting all types of counterfeit. Identifying counterfeit products requires a combination of analytical approaches, each targeting specific violations. For detecting adulteration in meat products, especially those containing poultry meat, polymerase chain reaction (PCR) is the most effective method. This review examines various types of food adulteration and analytical methods for their detection. Improving detection methods to ensure food safety is a key task for protecting consumer health. It is also necessary to strengthen responsibility for compliance with laws and regulations governing the quality requirements of meat products and preventing their falsification.
Keywords: adulteration; food safety; meat products; quality control; standard.

Introduction

Food safety is one of the key issues in modern society. With the rise in living standards, meat product consumption increases, creating conditions for food adulteration to reduce costs and gain illegal profits [1]. Dishonest producers resort to refilling, substitution, and other deceptive practices, leading to a rise in counterfeit products and a decline in meat quality. The most common method of meat adulteration is replacing expensive meats (such as beef and lamb) with cheaper alternatives (such as chicken or duck) or using inedible meat (e.g., fox or mink meat) [2]. Meat adulteration violates market regulations, infringes on consumer rights, and poses risks to health and safety. Counterfeit products may contain pathogenic microorganisms or toxic substances that cause poisoning, illness, or allergic reactions [3]. Additionally, meat adulteration disrupts religious traditions in Muslim countries, where the consumption of products containing pork or donkey meat is prohibited [4].

Therefore, one of the key tasks of food quality control laboratories is species identification of raw materials used in the food industry and determining the origin of meat in finished products. Verifying the authenticity of animal-derived food products is crucial for economic, sanitary, legal, religious, and medical reasons. Over the past decades, several incidents have occurred involving the use of unconventional meat types and wild animal meat. For example, in 1981, a major "meat substitution scandal" broke out when horse and kangaroo meat were discovered in shipments of Australian beef. In 2013, the "horsemeat scandal" emerged when horse and pig DNA were detected in beef burgers [5]. Such cases raise serious concerns about the authenticity and safety of animal-derived products, which is critically important for protecting consumer health. To prevent these risks, it is necessary to develop accurate and effective meat identification methods, enabling regulatory authorities to strengthen control measures and safeguard public health. Finding a fast, precise, convenient, and cost-effective method for determining meat composition remains a challenging task in the field of food quality control [6]. Traditional methods based on external characteristics (such as smell, color, texture, and taste), including organoleptic analysis and histological examination, do not allow for precise identification of the species composition of meat products. Protein-based analysis methods, such as ELISA and electrophoresis, also have limitations due to protein degradation during thermal processing. Unlike proteins, DNA remains stable even after food processing. Unlike proteins, DNA remains stable even after technological processing. Therefore, DNA-based methods are considered the most reliable for meat identification. These include PCR [7], multiplex PCR, fluorescent quantitative PCR, and the LAMP method, all of which provide high accuracy and reliability in determining the composition of meat products [8]. Despite the widespread use of advanced technologies such as digital PCR and CRISPR-Cas systems for food sample analysis, developing highly accurate analytical methods for detecting trace amounts remains a significant challenge. Based on the above, this research aims to analyze the current state of the adulteration of animal-derived food products, as well as the modern methods used for their accurate identification and reduction of adulteration. In accordance with the aim, the following objectives are addressed in the study:

- To provide a concise yet comprehensive overview that enables an understanding of the scale and key areas of food adulteration involving animal-derived products, thereby contributing to the more effective detection, prevention, and mitigation of such practices in the future;
- To offer readers the opportunity to analyze and critically evaluate existing approaches and methodologies used in the study of food adulteration and the techniques applied for its detection;
- To establish an informational foundation that facilitates the development of original scientific research focused on food adulteration issues, while avoiding unnecessary duplication of previously published works on this subject.

Types of Meat Product Adulteration

Food fraud has been known since ancient times, such as adding alum to bread or gypsum and starch to milk. With industrialization and market expansion, the diversity of food products has increased, leading to more complex adulteration schemes. Meat product fraud is among the most prevalent types of food adulteration. This is supported by data from 2013, which saw a peak in recorded fraud cases, coinciding with the horsemeat scandal. After 2013, the number of reported fraud cases remained consistently high over a 20-year period [9]. It can be assumed that the horse meat scandal exposed serious issues related to food fraud and highlighted the vulnerability of the global meat supply chain, particularly in raw meat, to counterfeiting [10].

A typical case of intentional meat adulteration is interspecies substitution, aimed at deceiving consumers by replacing expensive meat with cheaper alternatives, such as substituting beef with pork. Although this type of meat fraud rarely poses a health risk, it violates consumer interests and seriously hinders the development of the regional meat industry [11]. Sausages made from minced meat are particularly vulnerable to adulteration, as grinding meat hides its original morphological characteristics, making visual detection of fraud difficult. Due to price differences, cheaper meats such as pork, chicken, and buffalo meat are often used to substitute beef in meat products [12].

Studies in various countries have shown similar adulteration practices. For example, 25.6% (64 samples) of sausages containing chicken, pork, beef, and duck purchased from local markets in Sichuan, China, were adulterated. The most common form of violation in China was the addition of undeclared duck to products labeled as chicken or pork. In Italian markets, about 57% of packaged meat products, including sausages, pates, and meatballs, contained unlabeled pork, beef, and chicken ingredients. In

Turkey, it was found that sausages labeled as containing 5% beef contained no beef DNA, while a sample of 100% beef meatballs included chicken [13].

Another method of meat product adulteration is exceeding the permissible levels of food additives, particularly fiber. Increasing fiber content to 8% when the norm is 1–5% causes excessive moisture accumulation in the product and leads to loosening of the minced meat. A similar case occurred in 2017 when the Brazilian meat scandal involved various forms of adulteration, including the substitution of animal-derived ingredients, excessive addition of food additives, and water injection. Additionally, meat semi-finished products often use gelling and meat-replacing components. Partial or complete substitution of beef or lamb with cheaper offal or poultry meat is one of the most common methods of adulterating meat products. Moreover, this trend in the beef supply chain per-sists over time [14]. Numerous incidents of clenbuterol-contaminated meat products in China in 2011 threatened consumer health and undermined trust in food supplies [15].

Mislabeling of food products is also a serious form of fraud and can pose significant risks to consumer safety. An example is the mislabeling of toxic fish species, such as pufferfish, mackerel, and escolar (containing ciguatoxin), as safe species [16]. Cases have been reported where products labeled as squid turned out to be toxic pufferfish species. Such incidents not only posed serious health risks but also undermined consumer trust in the seafood industry [17]. A literature review indicates that the most common types of food fraud are mislabeling (20.7%), artificial enhancement (17.2%), and substitution (16.4%). Mislabeling is widely discussed in the literature and has been identified in 57% of processed meat products. The regions most affected by food fraud are Austral-ia (79% of mislabeled products) and South America (67%) [18].

Methods for Detecting Meat Product Adulteration

Quality control represents a system of standards aimed at ensuring food safety in accordance with consumer expectations and needs. Various parameters, including physical, chemical, microbiological, nutritional, and sensory properties, are used to maintain product safety. These quality indicators depend on factors such as taste, color, aroma, texture, and overall product perception. Chemical quality indicators depend on the content of sugars, proteins, fiber, as well as peroxide levels, free fatty acids, and enzyme activity [19]. One of the analytical methods used for food analysis is chromatography. This method is based on the interaction of analytes between the mobile and stationary phases, allowing for effective separation of substances. Methods are classified based on the type of stationary and mobile phases. The stationary phase is a solid material coated on a column through which the mobile phase is pumped. Compounds with minimal affinity for the stationary phase and short retention times elute first and are detected. However, despite the high accuracy of chromatographic methods, they are less effective for detecting adulteration in complex meat mixtures or thermally processed products. Additionally, their application is limited by the high cost of equipment and the complexity of sample preparation [20].

Gas chromatography is used for identification, authentication, and prediction of food quality characteristics. However, it requires sample derivatization due to the high boiling points and density of compounds. Liquid chromatography is used for identification, classification, and quality assessment of various food products. High-performance liquid chromatography (HPLC) allows for the analysis of polar and non-polar solutions without the need for derivatization. Chromatography is used for tocopherol analysis, amino acid determination, adulteration identification, detection of milk and cheese adulteration, and analysis of marker peptides in gelatins [21]. Chromatography, especially when combined with modern techniques such as spectrometry, remains one of the key tools for improving analysis accuracy and preventing food adulteration [22].

Mass spectrometry is a reliable and highly effective method for meat authentication, particu-larly in processed products containing meat from various mammalian and poultry species [23]. For example, pork-specific peptides can be used to differentiate pork from beef, goat, and chicken meat. Tandem mass spectrometry (MS/MS) can detect 0.55% pork in beef and 0.24% in processed beef [24]. The strategy of using peptide markers is based on proteomics, including enzymatic cleavage of specific peptide bonds in proteins. However, sample preparation for this method takes a significant amount of time: treatment with dithiothreitol to reduce disulfide bonds and iodoacetamide for thiol alkylation can take up to 24 hours. Thus, the complexity and duration of these preparation procedures limit the method's applicability for species identification in real meat products [25].

Immunochromatographic analysis (ICA) is a promising alternative and complement to traditional food analysis methods. This approach is based on the interaction of the target component with specific antibodies, followed by their separation on specialized membranes [26]. The advantages of ICA include speed, simplicity, low cost, specificity, and sensitivity. The analysis does not require complex sample preparation compared to more sophisticated methods. The main requirement for developing an ICA method aimed at assessing meat product composition is the selection of a suitable biomarker that can specifically recognize the tissue of a particular animal in the product. The suitability of a biomarker is determined by species specificity and resistance to degradation. Currently, widely used biomarkers include troponin I [27], myoglobin [28], hemoglobin [29], and immunoglobulin [30].

Food authenticity has become an important aspect of ensuring food safety and quality amid the increasing number of fraud cases and unethical practices reported worldwide in recent years. Various analytical methods of chromatography and spectroscopy, as well as molecular and immunological methods, have been developed to detect meat product adulteration [31-35]. Among molecular methods, special attention is given to PCR and real-time PCR, which are used for target DNA detection. In some countries, reverse transcription PCR (RT-PCR) is accepted as a standard method for meat authentication [36-38]. The scheme of one-step or two-step RT-PCR is shown in Figure 1.

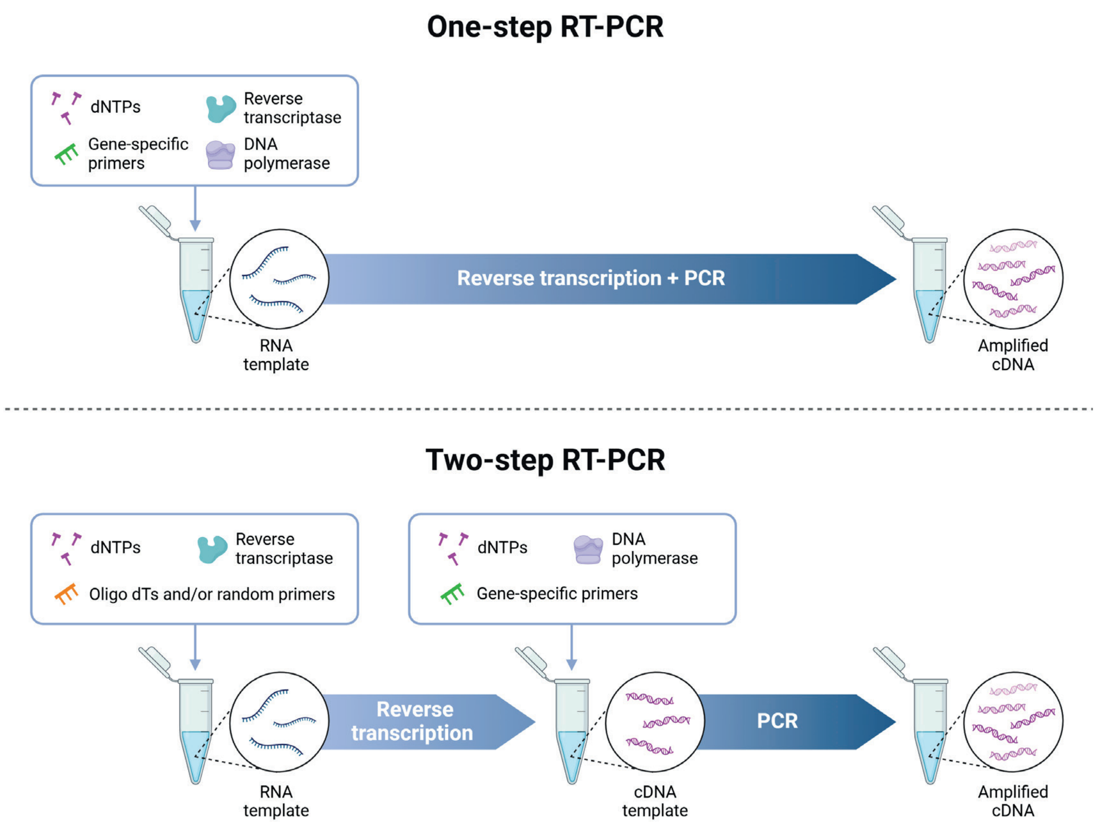

Figure 1 – Scheme of one-step and two-step RT-PCR

Multiplex PCR (mPCR) methods are convenient tools for simultaneous detection of multiple targets on a single platform. Due to their simplicity and low cost, enabled by standard agarose gel analysis, they have become widely used in the food industry [39]. However, as the number of pri-mers and reaction complexity increases, the likelihood of mutual interference between components, such as templates and primers, increases, which can reduce amplification efficiency or cause complete failure [2]. Currently, most mPCR methods are limited to detecting 8 to 12 animal sources on a single platform in one reaction. Only one method is known to identify 12 meat ingredients using universal primers [40]. Primer specificity is a key condition for successful mPCR. To ensure accurate species identification, primers must demonstrate strict specificity to target species and significant mismatch with non-target species [41]. Even a single base pair mismatch at the 3' end of primers can significantly reduce amplification efficiency [42]. Therefore, there is an urgent need to develop rapid, sensitive, and reliable analytical methods for identifying various meat species in meat products [43].

Innovative Technologies in Combating Adulteration

In recent years, with the improvement of video surveillance systems and increased computational capabilities, imaging methods have demonstrated potential for non-contact detection of food adulteration [44]. Imaging is a non-contact method based on optical principles that provides complete information about objects, including their chemical properties and sensory characteristics. This plays a key role in assessing the external properties of food products. Among modern imaging methods used for meat quality and safety analysis, hyperspectral imaging (HSI), X-ray imaging (RI), and thermal imaging (TI) can be highlighted [45].

Compared to traditional chemical analysis methods, near-infrared spectroscopy (NIRS) offers advantages such as high speed, non-destructive nature, and low cost. This method is widely used for chemical composition analysis, food quality assessment, and adulteration detection [46, 47] Their results showed a high degree of correlation with data obtained by ICA methods [48, 49].

The application of Raman spectroscopy for meat quality and safety assessment covers aspects such as spoilage, adulteration, and other issues. The use of the similarity index (SI) in meat spectros-copy has proven effective as an alternative tool for classification, allowing differentiation of meat samples from the same animal species but different origins. The main advantage of SI is its simplicity and accessibility for non-specialists, enabling the use of this method in the industry by employees with varying levels of training to track meat origin [50]. Terahertz spectroscopy (THz spectroscopy) has the ability to identify meat from different tissues, grades, or even brands of the same grade, creating a theoretical and experimental basis for verifying meat authenticity and detecting adulteration in practical applications [45].

The combination of thermal imaging and a high-precision convolutional neural network enables the detection of lamb mince adulteration with pork and the addition of flavoring essence to lamb [51]. Additionally, thermal imaging can be used to predict chicken meat temperature after cooking. Combined with multilayer neural networks, this technology demonstrates significant potential in assessing beef quality [52]. The integration of mathematical processing of chemical data with instruments such as an infrared spectroscopy source and metal-oxide-semiconductor sensors ("electronic nose"), the schematic of which is shown in Figure 2, has great potential for detecting meat adulteration.

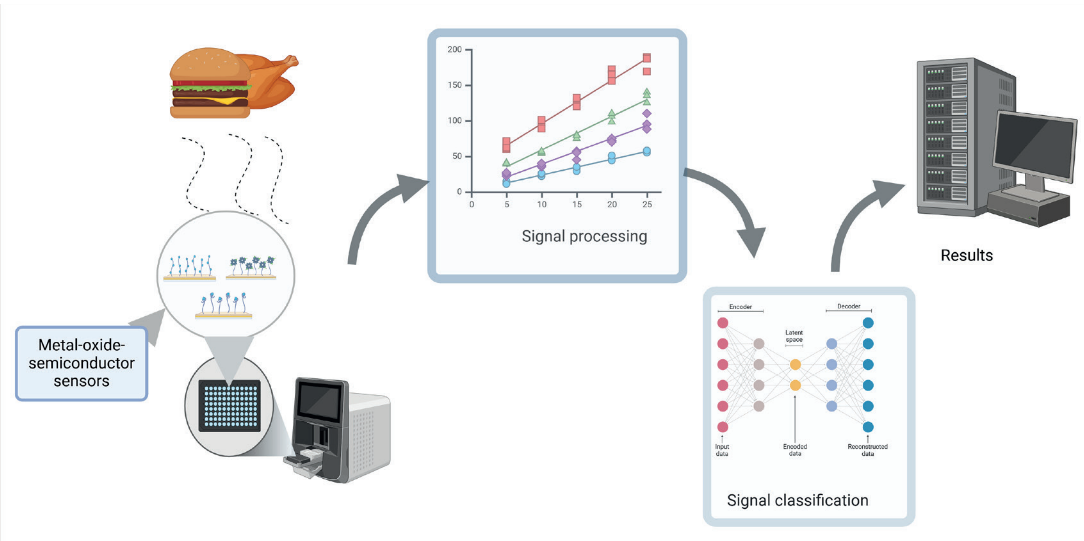

Figure 2 – Scheme of the "Electronic Nose" System

However, both approaches have their limitations, and their combined use remains relatively rare. Therefore, the development of more accurate, rapid, cost-effective, and universal technologies for detecting meat adulteration is one of the priority areas for future research [53]. Other studies have demonstrated the effectiveness of using an "electronic nose" for analyzing chicken and beef seasonings, as well as predicting their sensory attributes. The method proved effective for identification processing and storage violations in sausages and can extract flavor "fingerprints" of products [54].

Currently, for freshness assessment, adulteration detection, odor analysis, and detection of specific compounds in meat products, there is a widely used non-destructive detection technology (NDDT) [55]. This technology plays a key role in ensuring meat quality and safety, becoming one of the most important tools in food control. Compared to traditional methods, NDDT has clear advantages, such as higher efficiency and no impact on the test object, making it promising for wide-spread use in meat product control [56]. Despite the rapid development of spectroscopic and imaging methods, they face several limitations. Spectroscopic methods require a significant amount of physicochemical experiments before the modeling stage, and models need to be regularly updated depending on sample classes and conditions [57].

Regulatory and Legal Framework

Meat product adulteration is regulated by international standards and national legislation in various countries. The key aspects focus on ensuring product quality, food safety, and consumer protection. The primary international standard is the Codex Alimentarius, which sets global food safety standards, including those for meat and meat products. This code regulates labeling, species identification, the use of additives, and analytical methods for detecting adulteration [58]. Another international standard is ISO 22000 (Food Safety Management Systems), which sets requirements for producers in identifying and preventing adulteration. ISO 22000 is intended to replace HACCP (Hazard Analysis Critical Control Points) in food safety matters. The main difference is that in ISO 22000, systems such as Good Manufacturing Practice and Good Hygiene Practice are prerequisites, leading to fewer critical control points [59]. The international standard ISO 17025 establishes requirements for laboratories engaged in product testing, including the detection of meat adulteration.

Among national laws and standards, European legislation is noteworthy. The European Union is known for its strict food safety standards, which are among the highest in the world. The EU has developed comprehensive legislation aimed at protecting consumers and ensuring food and feed safety. The key regulatory document is the General Food Law Regulation (EC No 178/2002), which establishes the basic principles, objectives, and requirements for food safety. According to this regulation, the European Food Safety Authority (EFSA) was established, beginning operations on January 1, 2002, and located in Parma, Italy. The agency serves as an independent body providing scientific advice to EU policymakers on food chain safety. Regulation (EU) No 1169/2011 on food labeling requires the indication of meat species, country of origin, and composition, while Regulation (EU) No 853/2004 regulates sanitary standards for production and control [60].

In the United States, the Food Safety and Inspection Service (FSIS) of the U.S. Department of Agriculture (USDA) plays a key role in regulating meat product safety. FSIS oversees for meat quality, poultry, and eggs, including their processing and labeling. FSIS programs regulate the safety and quality of meat and poultry products intended for public consumption, as well as proper labeling for interstate or international markets [61, 62].

In Kazakhstan, the regulation of meat product falsification is based on national legislation, as well as international standards adopted within the framework of the Eurasian Economic Union (EAEU). The main aspects of control include safety, quality, and transparency of information about product composition. Technical Regulations (TR) of the Customs Union (CU) TR CU 034/2013 "On the Safety of Meat and Meat Products" establishes mandatory safety requirements, including control over the content of harmful substances, identification of meat and its origin. It prohibits the use of substitutes (e.g., soy or starch) without indication on the label and describes methods for analyzing the composition of meat products. TR CU 022/2011 "Food Products in Terms of Labeling" requires manufacturers to specify product composition, meat type, ingredient proportions, and country of origin. It also prohibits misleading consumers (e.g., claiming one type of meat is used when another is actually present). In addition to EAEU standards, Kazakhstan also applies ISO 22000 and ISO 17025 standards [60].

From the national legislation of Kazakhstan, it is important to note the Code of the Republic of Kazakhstan "On Public Health and the Healthcare System". This regulation aims to prevent the falsification of food products, including meat, and contains requirements for the quality and safety of food products, as well as their sanitary and epidemiological examination. The Law of the Republic of Kazakhstan "On Consumer Rights Protection" obliges the provision of accurate information about the composition and quality of products and provides for liability for violations of consumer rights in case of falsification. The requirement for product compliance with technical regulations is governed by the Law of the Republic of Kazakhstan "On Technical Regulation" and National Standards ST RK. These documents contain requirements for the quality of meat and meat products, harmonized with international standards [60].

Conclusion

The falsification of meat and meat products remains one of the most significant problems in the food industry, affecting economic, social, and environmental aspects. This phenomenon under-mines consumer trust, harms honest producers, and creates health risks due to the use of undeclared, low-quality, or hazardous ingredients. The main forms of falsification include substituting one type of meat for another (e.g., using pork instead of beef), adding unacceptable ingredients (water, starch, soy proteins) without indication on the packaging, and selling expired products as fresh. Such violations complicate the identification of product origin and may threaten consumer health due to the potential presence of allergens, microbial contaminants, or chemical substances.

To effectively address the problem of falsification, a systematic approach is required, including laws establishing clear requirements for labeling, quality, and safety of meat. Examples of successful practices can be found in EU regulations, such as EC No 178/2002, which ensure a high level of consumer protection. In Kazakhstan and EAEU countries, technical regulations are in place, but their constant adaptation to modern challenges is necessary.

The use of advanced technologies, such as DNA analysis to determine the species composition of meat, physicochemical studies to identify additives, and high-precision methods for detecting microbial and chemical hazards, significantly enhances control effectiveness. Laboratories certified to international standards (e.g., ISO 17025) play a key role in identifying falsifications. The use of technologies such as blockchain can help create transparent supply chain tracking systems, where each stage of production and processing is recorded and protected from falsification.

The global problem of falsification requires the exchange of experience and data between countries. An example is the activities of the EFSA, which coordinates the work of national agencies and scientific centers. Such exchanges allow for the unification of standards and the development of joint methods to prevent violations. Producers must bear strict responsibility for non-compliance with standards. The introduction of significant fines, product recalls, and criminal penalties for falsification can be effective tools in combating violations. Additionally, it is important to ensure production transparency, up to tracking the origin of raw materials, so that consumers can be confident in the quality and safety of the products they purchase. Raising public awareness about the signs of quality products and potential risks of falsification also plays a significant role. Informed consumers can recognize violations, choose more reliable products, and support honest producers.

Thus, only a comprehensive approach combining the efforts of government authorities, producers, the scientific community, and consumers themselves can effectively combat meat falsification. Solving this problem will not only improve public health and strengthen trust in the food industry but also contribute to the creation of a more sustainable, transparent, and fair system of meat production and trade.

Authors' Contributions

SB; KM and AB: Designed and supervised the study, conducted a comprehensive literature search, analyzed the gathered data and drafted the manuscript. KT: Statistical and bioinformatic analysis, and drafted the manuscript. SS: Conducted study and bioinformatic analysis. All authors have read, reviewed, and approved the final manuscript

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Conflicts of Interest

The authors declare that they have no competing interests.

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