Food Science of Animal Products

Review Article

Development of non-thermal processing technologies based on physical electro-effects for red meat products and human health: past, present, and future

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Received: March 21, 2026; Revised: April 29, 2026; Accepted: June 29, 2026

Abstract: As an important proteins source in human diet, the processing methods of red meat significantly impact its nutritional value, safety, and sensory quality. Traditional red meat processing methods through heating frequently lead to significant nutrient loss, undesirable flavor changes, and the generation of detrimental compounds. With the advent of the era of human electrification, electro-effects non-thermal physical processing technologies—represented by electrical stimulation, pulsed electric field, ohmic heating, high-voltage electrostatic field, and ultraviolet radiation have garnered significant attention for their potential to enhance meat quality without substantial temperature elevation. This review delves into the developmental history, mechanisms of action, and future application prospects of these technologies within red meat food science and human health. Building upon past research, this paper focuses on analyzing the effects of electro-effect technologies on the biochemical, molecular biological, and microbiological characteristics of red meat. This includes their key roles in enhancing tenderness, color, water-holding capacity, flavor, protein digestibility, and microbial control. It also explores the diverse applications, technological synergies, and challenges these techniques face in advancing red meat products toward greater nutritional value, safety, palatability, and sustainability.

Keywords: red meat; physical electrical effects; non-thermal processing; electrical stimulation; pulsed electric fields

Citation: J. T. Wen, L. Yang, Y. P. Gao, et al., Development of non-thermal processing technologies based on physical electro-effects for red meat products and human health: past, present, and future, Food Sci. Anim. Prod. 4 (2026) 9240186. https://doi.org/10.26599/FSAP.2026.9240186.

1 Introduction

Red meat-including beef, pork, lamb, and venison-serves as a vital component of the global diet, functioning as an important source of high-quality protein, essential amino acids, B vitamins, iron, zinc, and other key nutrients[1]. In response to the growing consumer demand for enhanced food quality, health benefits, and safety, conventional red meat processing techniques such as high-temperature cooking, curing, and freezing are increasingly being re-evaluated. These methods are associated with several drawbacks, including nutrient loss, undesirable flavor alterations, texture degradation, and high energy consumption. Consequently, food scientists are shifting toward developing milder, more efficient, and sustainable alternative processing technologies[2–4]. Notably, traditional red meat processing not only has the aforementioned quality-related issues but some processing methods may also pose potential health risks. Studies have shown that the thermal processing of red meat and its related physiological mechanisms may be associated with the occurrence of cancer[5], and its digestion process may also produce biological and molecular characteristics related to the development of colorectal cancer[6], and even form DNA adduct markers associated with gastrointestinal digestion[7]. Red meat intake induces an increase in *N*-nitroso components production in the digestive tract. Additionally, two genotoxic compounds causing DNA damage—heterocyclic aromatic amines (HAAs) and polycyclic aromatic hydrocarbons (PAHs)—are present in high-temperature cooked meat and smoked or grilled meat, respectively. HAAs and PAHs as a possible mechanism increasing colon cancer risk in the context of red meat intake[8], which further highlights the necessity of developing new healthy processing technologies.

Against this backdrop, electricity-based non-thermal technologies have emerged as innovative and promising tools that are progressively reshaping the landscape of red meat processing. By applying electric fields, these techniques induce physical and biological changes in meat products, enabling microbial inactivation, modulation of enzyme activity, structural modification, and improved mass transfer-all without substantially increasing the temperature. These advantages contribute to enhanced nutritional quality, extended shelf life, and improved sensory properties of red meat[4–5,9]. Prior to this, relevant studies have mostly focused on post-mortem tenderization of hot-boned or chilled meat, or pre-treatment of frozen meat prior to freezing, with the core goal limited to improving the initial texture of raw meat[2]. No comprehensive regulatory system covering the entire production cycle of fermented meat products has been established. This review focuses on four major electricity-based non-thermal technologies: electrical stimulation (ES), pulsed electric fields (PEF), ohmic heating (OH), and high-voltage electrostatic fields (HVEF).

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It systematically traces their evolution in the context of red meat science and human health-from initial concepts and early-stage applications to current research trends and industrial implementation, as well as future opportunities and challenges. Furthermore, this article provides a critical analysis of how these technologies affect red meat quality across multiple dimensions (biochemical, molecular, microbiological, and technological) and explores their underlying mechanisms in regulating key attributes such as nutrition, flavor, and safety.

2 Evolution and development of non-thermal processing technology based on physical electrical effects: past and present

The application of electric field technology in food processing dates back to the early 20th century, when low-voltage alternating current electric fields were initially explored for milk pasteurization to enhance food safety and extend shelf life[4]. The primary factors contributing to meat spoilage include microbiological spoilage, enzymatic spoilage, lipid oxidation, and protein oxidation. Among these, oxidative processes along with hydrolytic reactions induced by bacteria and enzymes constitute the predominant mechanisms of meat deterioration[10]. And in 2022, the academic community proposed a foundational theoretical concept: alternating current electric fields possess the capability to disrupt biological cell structures, a process termed "electro-plasma dissolution"[11]. These early explorations laid the groundwork for the development of modern non-thermal processing technologies based on electrical effects (Figure 1).

2.1 Early applications of ES in red meat tenderization

ES represents one of the earliest and most widely adopted physical electrical effect technologies in red meat processing. Its core principle involves applying a specific current intensity to carcasses immediately post-slaughter, accelerating post-mortem muscle glycolysis through physical intervention. The development and application of ES technology originated from addressing the issue of "cold shortening" in meat processing. When carcass pH decreases slowly while muscle temperature remains relatively high, premature chilling induces excessive myofibril contraction, resulting in tough meat and poor taste[1] (Figure 2).

ES accelerates adenosine triphosphate (ATP) depletion, prompting muscles to rapidly enter the tetanic stage and enhancing lactic acid accumulation as a glycolytic byproduct, thereby causing a swift pH decline[1]. This acidification inhibits the activity of calmodulin-binding proteins, thereby preventing excessive muscle contraction caused by ATP depletion in cold environments[12].

ES is believed to activate the endogenous proteolytic enzyme system in muscles by influencing calcium ion release from the

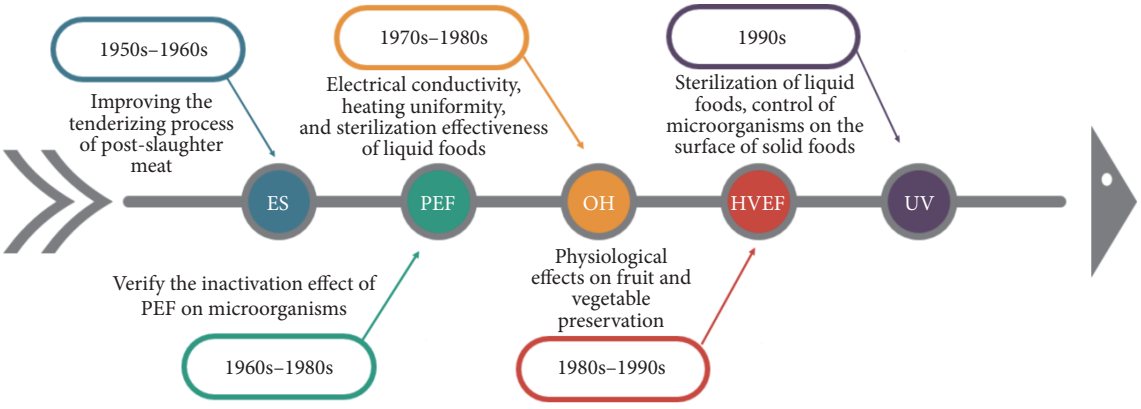


Figure 1 Several early applications of non-thermal processing.

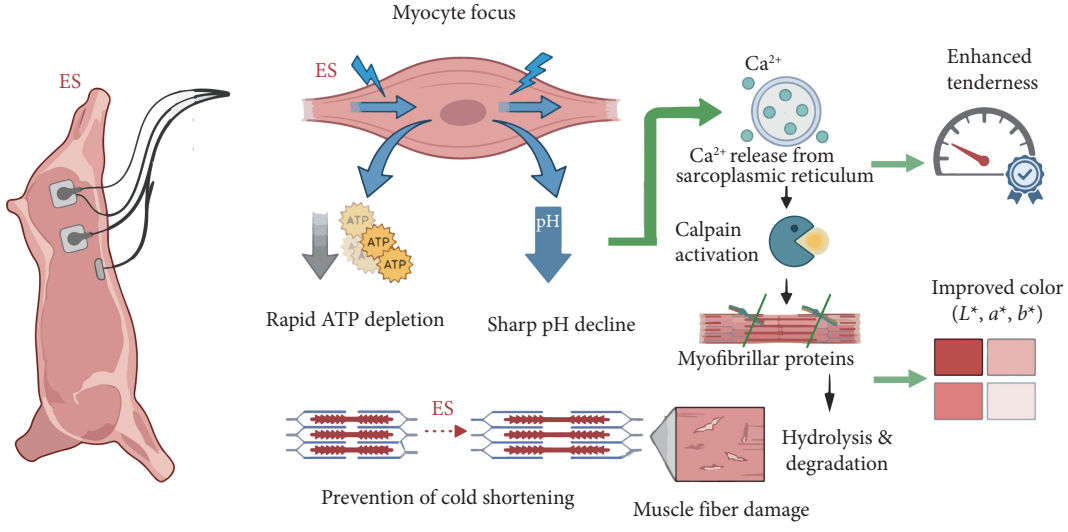


Figure 2 ES technical diagram. L^*, brightness value; a^*, redness value; b^*, yellowness value.

sarcoplasmic reticulum, particularly activating calpains (calcium-dependent proteases). These enzymes degrade myofibrillar proteins (e.g., troponin-T and tropomyosin), enhancing meat tenderness[1,3]. Studies indicate that ES-generated currents may cause microscopic damage to muscle fiber structures, leading to rupture and enhanced tenderness[1,3].

Extensive research data validate ES's effectiveness in improving red meat tenderness and color. Its applications span various red meat types, including alpaca, beef, sheep, and deer. For instance, studies on South American camelids demonstrate that ES significantly enhances alpaca meat tenderness (reducing shear force) and improves color (increasing L^*, b^*, and a^*)[1]. Similar improvements in L^* and a^* are observed in lamb and goat meat, while ES's positive effects on beef color stability and visual quality are also confirmed[13].

2.2 PEF technology

2.2.1 The rise of PEF technology

PEF technology, a typical non-thermal processing method, originated 65 years ago in sugar beet extraction processes[11]. Its technical principle involves applying short-duration (microseconds to milliseconds) and high-intensity (10–80 kV/cm) electrical pulses to food without significantly raising its temperature[3,14]. Initially applied to liquid foods[15] (e.g., juice and milk), PEF technology has recently expanded to solid foods, including meat, vegetables, and seafood[3,14]. It is primarily used in meat processing after rigor mortis sets in, it utilizes the electroporation effect to disrupt cell membranes, thereby accelerating the brine penetration and drying processes.

2.2.2 Core mechanism of PEF technology: electroporation

PEF technology induces reversible or irreversible pores on cell membranes, significantly enhancing membrane permeability[3–4,14]. For microorganisms, this disruption of membrane integrity causes leakage of intracellular ions and small molecules, collapse of the transmembrane potential, and ultimately leads to cell death. This mechanism enables multifaceted food processing functions: 1) It inactivates microorganisms by disrupting cell membranes and causing the cell contents to leak out, thereby improving food safety[4,14]. 2) Reduce or inactivate enzyme activity, thereby preventing a decline in food quality and deterioration[4,14]. 3) PEF technology accelerates substance exchange (e.g., salt, spices, bioactive compounds) within and between cells, facilitating rapid pickling or extraction of valuable compounds from by-products[34]. 4) Alter the structure of muscle fibers[16], increase tissue suppleness, and improve the digestibility and solubility of proteins[3] (Figure 3).

2.3 OH technology

2.3.1 Development of OH technology

OH is a food heat processing technology based on the Joule effect, utilizing the inherent resistance of food to convert electrical energy directly into heat energy when current passes through it[24]. Unlike traditional heat conduction or convection methods, OH achieves rapid and uniform heating by generating heat internally, reducing processing time[9]. Therefore, OH shows unique usefulness in rapid thawing under controllable thermal effects (without causing thermal denaturation of meat). Microbial inactivation occurs through thermal effects, elevated temperatures denature microbial proteins, inactivate enzymes, and disrupt membrane lipid bilayer structures[17] (Figure 4).

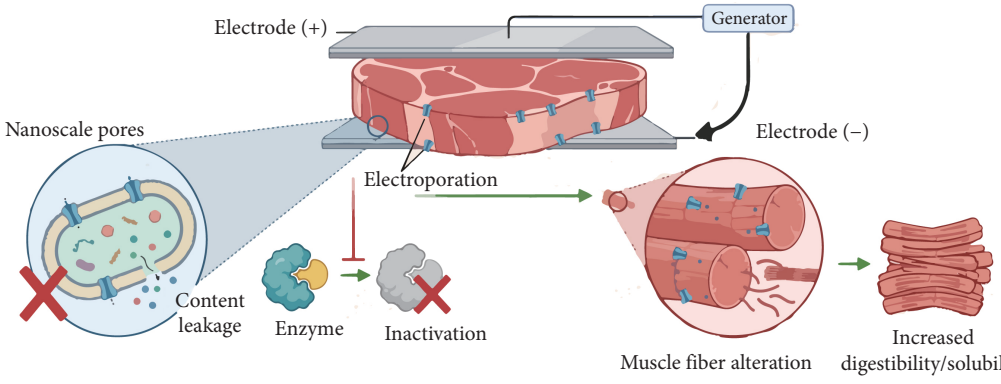


Figure 3 PEF technical diagram.

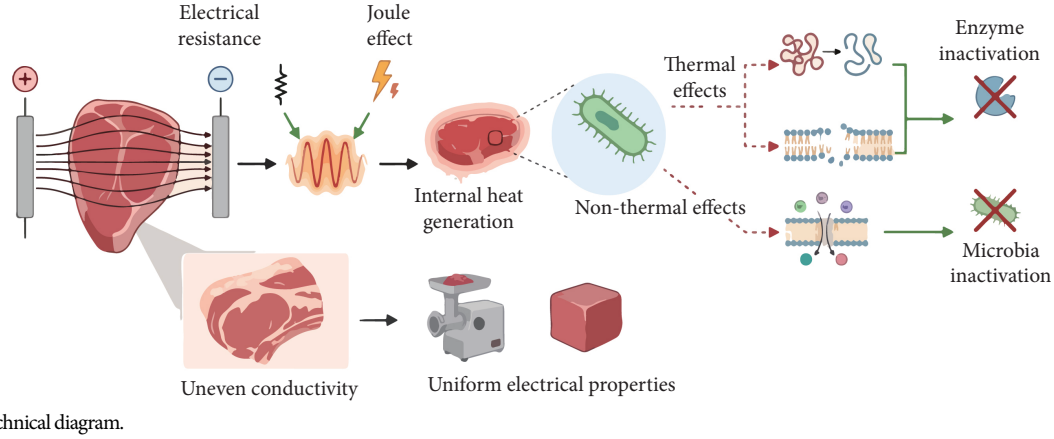


Figure 4 OH technical diagram.

2.3.2 Unique technical characteristics and advantages of OH technology

Direct current passage avoids overheating or cold spots caused by uneven heat conduction in traditional methods, better preserving food flavor and nutrients[24]. OH efficiently inactivates microorganisms through thermal effects and non-thermal effects (e.g., changes in cell membrane permeability), enhancing inactivation efficacy[4]. OH reduces meat cooking loss, enhances juiciness, and promotes flavor substance formation (e.g., Maillard reaction)[2].

OH application in meat products remains limited due to uneven electrical conductivity, particularly in high-fat meat, leading to uneven heating[24]. However, processing ground meat or meat cut into specific shapes can significantly expand the scope of OH's applications in the meat processing industry[9].

2.4 HVEF technology

2.4.1 Application of HVEF

HVEF technology utilizes non-uniform or electrostatic fields to act on food. Unlike PEF and OH, HVEF operates at lower currents, influencing food quality through physical mechanisms other than Joule heating (means OH)[9,18]. HVEF shows potential in freezing, thawing, and drying processes.

2.4.2 Physical mechanisms of HVEF in food quality regulation

HVEF induces water molecule polarization and rearrangement, influencing ice nucleus formation and generating finer, more uniform ice crystals, reducing meat tissue damage and minimizing water loss during thawing[9,18]. Corona discharge in non-uniform HVEF generates "corona wind", containing active particles and free radicals that accelerate food drying and thawing[9]. HVEF affects microbial membrane potential and esterase activity, demonstrating bactericidal effects while potentially altering enzyme conformations to regulate activity[9,18] (Figure 5).

HVEF inhibits lipid oxidation, slows nucleotide degradation, and reduces protein autolysis in aquatic products (e.g., shrimp), improving flavor and extending shelf life[18]. Although direct HVEF application research in red meat is scarce, these mechanisms provide a theoretical basis for its potential in red meat quality preservation and enhancement.

2.5 UV radiation technology: a new option for non-thermal sterilization

UV radiation technology is a non-thermal physical sterilization method that inactivates microorganisms by emitting specific wavelengths of UV rays, destroying their genetic material (DNA/RNA). UV radiation is classified into UVA, UVB, and UVC, with UVC (200–280 nm) being most widely used in food processing due to its strong sterilization ability[19]. The purine and pyrimidine bases in microbial DNA and RNA strongly absorb UVC photons, forming photoproducts such as thymine dimers[19]. This blocks DNA replication and transcription, leading to microbial inactivation (Figure 6).

UV technology development in red meat processing focuses on inactivating surface microorganisms and extending shelf life. UV irradiation significantly reduces pathogenic bacteria (e.g., *Salmonella*, *Escherichia coli*, *Listeria*) on meat surfaces with minimal impact on internal meat color, pH, and sensory characteristics. However, UV's limited penetration power restricts its use to surface sterilization. Recent advancements in ultraviolet-light emitting diode (UV-LED) and pulsed light (PL) technologies have improved UV radiation stability and efficiency, enabling controllable wavelength generation and new possibilities for meat surface disinfection.

2.6 Influencing factors

The effectiveness of physical electrical effect non-thermal processing techniques is influenced by various factors: 1) electrical field parameters, such as electric field intensity, pulse width, frequency, processing time, and specific energy directly determine processing efficacy. 2) Meat properties, such as meat type (beef, pork, chicken), muscle fiber type, connective tissue content, fat content, pH, and electrical conductivity affect electric field distribution and interaction effects[20–22]. 3) Equipment design, such as treatment chamber geometry, electrode materials, and spacing influence electric field uniformity and processing efficiency[23]. 4) Environmental conditions, such as processing temperature, pressure, and synergy with other technologies significantly impact final outcomes.

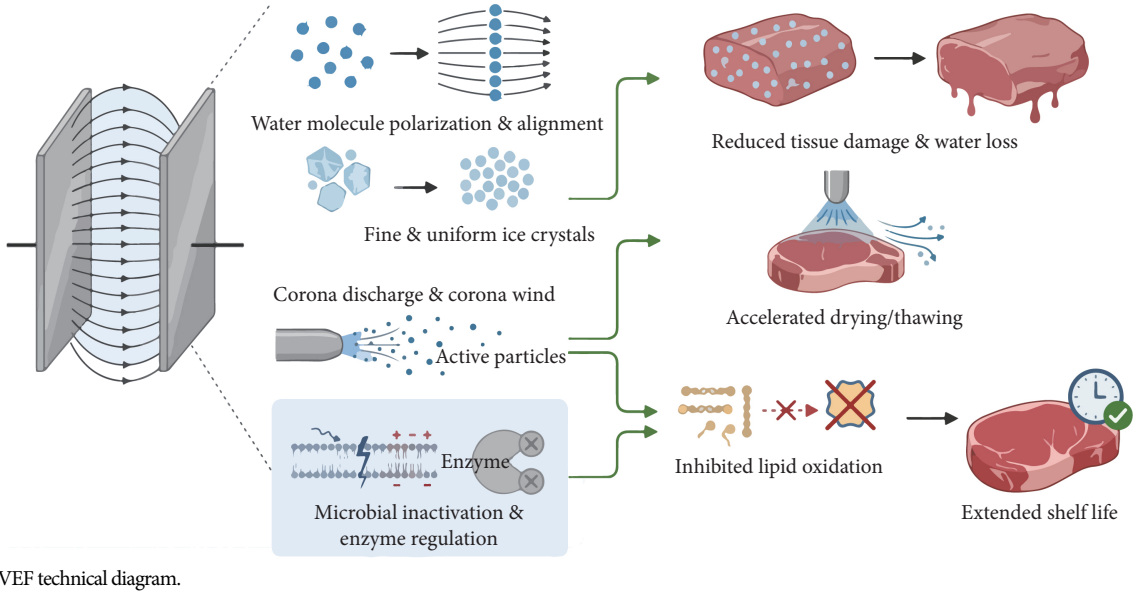


Figure 5 HVEF technical diagram.

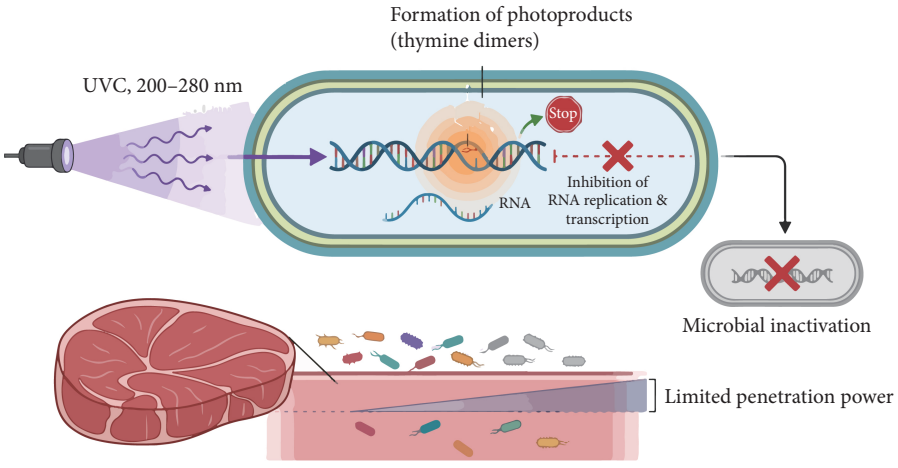


Figure 6 UV technical diagram.

3 Effects of physical electrical non-thermal processing technologies on red meat quality: mechanisms involved

Physical electrical non-thermal processing technologies exert a profound impact on red meat quality, with their mechanisms encompassing intricate biochemical, molecular biological, and microbiological processes. Understanding these mechanisms is pivotal for optimizing technological applications and developing new products (Table 1).

3.1 Biochemical and molecular biological mechanisms

The biochemical and molecular biological effects of electric fields on red meat primarily focus on cell membrane structure, protein conformation, enzyme activity, and metabolites.

3.1.1 Tenderness and protein structure

Tenderness is one of the most valued meat quality attributes by consumers. Postmortem aging of meat generates bioactive peptides through the hydrolysis of muscle proteins, which may exert different physiological regulatory activities to promote consumer health, while simultaneously improving tenderness[30]. Electrical effect technologies significantly enhance red meat tenderness through multiple pathways. The core mechanism of PEF and ES is electroporation, which forms pores on the muscle cell membrane, increases cell permeability, and triggers the release of intracellular calcium ions[20,31]. The release of calcium ions activates the endogenous proteolytic enzyme system, particularly calpains, thereby accelerating the degradation of myofibrillar proteins (such as troponin-T and desmin)—a key process in post-mortem aging and tenderization of meat[3]. Additionally, high-intensity electric fields can directly cause physical damage to myofibers and connective tissues, such as sarcomere elongation, *Z*-disk rupture, and collagen fiber structure weakening[3,32]. PEF treatment has also been shown to lower the denaturation temperature of collagen in connective tissues and increase its thermal solubility, which is particularly important for softening tough meat cuts rich in connective tissues (e.g., beef brisket) and effectively shortening cooking time[26].

Electrical effect technologies can also induce partial unfolding or denaturation of proteins. This structural change makes proteins more flexible and open, exposing more enzyme cleavage sites that were previously masked. Consequently, it enhances the sensitivity of proteins to gastrointestinal digestive enzymes (such as pepsin and trypsin), significantly improving the protein digestibility and soluble protein content of meat products[11,27].

Table 1 Mechanisms of action of electrical non-thermal processing technologies on red meat quality.

Mechanism of action	Related technologies	Main impact	References
Cell membrane electroporation	PEF, OH	Enhances cell membrane permeability, leading to the leakage of intracellular substances, which is crucial for tenderization and microbial inactivation	[4,14,24]
Calpain activation	ES, PEF	Electroporation-induced calcium ion release activates calpains, degrading myofibrillar proteins and improving tenderness	[1,3,25]
Physical disruption of myofibers/connective tissues	ES, PEF	High-intensity electric fields directly disrupt myofibrillar structures, reduce the thermal stability of connective tissues, and enhance tenderness	[3,26]
Protein unfolding/denaturation	PEF, OH	Partial unfolding of proteins exposes enzyme cleavage sites, increasing protein digestibility and solubility	[11,27]
N-Glycolylneuraminic acid (Neu5Gc) molecular destabilization	ES	Alters the molecular structure of Neu5Gc, rendering it unstable and significantly reducing its content in red meat	[28]
Lipid/protein oxidation	PEF, UV	The impact of PEF on lipid oxidation remains controversial; UV radiation may induce oxidation; lipase activity is induced through the disruption of cell structures, facilitating lipid oxidation	[11,19]
Nucleotide/amino acid metabolism/damage to the bacterial cell wall	HVEF	Inhibits nucleotide degradation, improves flavor, and slows down autolysis, leakage of intracellular components	[18,29]

3.1.2 Flavor, color, and harmful substances

Electrical effect technologies exert complex influences on the flavor and color of red meat. By enabling rapid and uniform heating, OH effectively prevents excessive oxidation of lipids and proteins, thereby better preserving the original flavor of meat[2]. Through enhancing mass transfer, PEF can promote the formation and release of flavor precursor substances. For instance, PEF pretreatment of air-dried duck meat increases the content of umami and sweet amino acids, as well as the concentration of key aroma compounds[33]. However, the effects of PEF on lipid oxidation remain controversial. Some studies suggest that PEF induces the production of reactive oxygen species, which leads to oxidative damage to unsaturated lipids, increases the concentration of lipid oxidation products, and exacerbates lipid oxidation[34]. Such as PEF (600 V/cm, 10 ms) had a negative effect on the stability of primary and secondary lipid oxidation products in sea bass samples[35], while others show no significant effect[11]. Such as, under conditions of 1–1.4 kV/cm, 20 ms, and 90 Hz, the lamb meat does not oxidize immediately[36]. In terms of color, ES and PEF can improve meat L^* and a^*, but high-intensity treatment may cause color darkening due to myoglobin oxidation[1,11,25].

In terms of human health, it has been found that ES can significantly reduce the content of Neu5Gc, a harmful substance in red meat associated with chronic inflammation[6]. Applying a 120 V, 50 s ES to beef tenderloin that had been frozen at −20 ℃ reduced the Neu5Gc content in the meat samples by 74.24% with minimal impact on meat quality. When the voltage reached 50 V, the Neu5Gc content showed a slight change; as the voltage continued to rise, the Neu5Gc content continued to decrease; and when the voltage reached 300 V, the Neu5Gc content was significantly lower than in all previous treatment groups. Therefore, as the electric field strength increased, the degradation effect also intensified. Conceptual density functional theory suggests that ES can directly affect the Nue5Gc molecule through charge transfer and induced polarization effects, causing it to become unstable and leading to its degradation[28].

3.1.3 Water-holding capacity

Water-holding capacity is a key indicator affecting meat juiciness and processing yield. The impact of electrical effect technologies on water-holding capacity is relatively complex. By modifying cell membrane permeability through electroporation, PEF's effect on water-holding capacity is controversial. Some studies suggest that PEF can improve water-holding capacity and reduce drip loss[34,37], possibly because water molecules are trapped in hydrophilic pores or protein conformational changes enhance their interaction with water. However, other studies indicate that high-intensity PEF may increase drip loss and cooking loss due to irreversible damage to the cell membrane[11,31]. In contrast, OH technology generally reduces cooking loss and enhances meat juiciness[2,21].

3.2 Microbiological and food safety mechanisms

Ensuring the microbiological safety of red meat is a top priority during processing. Physical electrical non-thermal processing technologies provide effective non-thermal sterilization methods (Table 2).

PEF and OH generate nanoscale pores, namely electroporation, on microbial cell membranes, disrupting their permeability barrier and causing leakage of cellular contents, thereby achieving microbial inactivation[4,34,38].

UV radiation, especially in the UVC band, directly damages microbial DNA and RNA molecules, forming pyrimidine dimers, thereby inhibiting gene replication and expression and ultimately leading to microbial death[19]. UV radiation is mainly applicable for surface sterilization of meat products. Although its penetration capacity is limited, it is highly effective in controlling surface contamination[19]. Inactivation efficiency is influenced by various factors, including electric field parameters (intensity, frequency, number of pulses), UV dose and wavelength, microbial species (Gram-negative bacteria are generally more sensitive than Gram-positive bacteria), cell size and morphology, as well as the physicochemical properties of the food matrix (such as pH, electrical conductivity, and composition)[4–5,19].

ES inactivates microorganisms primarily by disrupting the integrity of the microbial cell membrane through electroporation. In addition, it directly interferes with membrane potential and ion channel function, thereby disrupting electrophysiological homeostasis and signal transduction, which leads to metabolic disorders and programmed cell death[40,42]. For instance, ES damages the electron transport chain, which is predominantly localized on the bacterial inner membrane and mediates ATP production, consequently blocking cellular respiration, physiological pathways, and growth capacity[41].

These non-thermal sterilization methods effectively inactivate various pathogenic and spoilage bacteria, extend the shelf life of red meat products, and avoid quality deterioration caused by traditional thermal processing[43], thereby significantly enhancing food safety of red meat products while reducing reliance on chemical preservatives.

Table 2 Microbial inactivation mechanisms and corresponding technologies.

Technology	Microbial inactivation mechanism	Key characteristics and limitations	References
PEF/OH	Electroporation of microbial cell membranes causes leakage of cellular contents and subsequent cell death	PEF is highly efficient and non-thermal but has limited penetration in solid meat; OH combines thermal and non-thermal effects, achieving more thorough sterilization	[4,14,38–39]
UV radiation	UVC radiation directly damages microbial genetic material, forming pyrimidine dimers and inhibiting gene replication	Primarily suitable for surface sterilization with weak penetration, UV-LED and PL technologies have improved efficiency and controllability	[10]
HVEF	Alters microbial membrane potential and enzyme activity; active substances in the corona wind also exert bactericidal effects	Research is still in the early stages, with relatively mild bactericidal efficacy	[9,18]
ES	Through the electron transport chain that mediates ATP production; electroporation damages the microbial cell membrane	It is non-thermal, highly efficient, and highly controllable, making it suitable for the inactivation of drug-resistant bacteria and the sterilization of heat-sensitive materials	[40–42]

4 Future prospects and applications

The growing consumer demand for healthier and higher-quality food products, combined with the increasing emphasis on sustainable development in the food industry, highlights the substantial potential of electricity-based non-thermal processing technologies in the red meat sector. Future advancements are anticipated to concentrate on diversified applications, technology integration, and intelligent processing.

4.1 Diversified applications and product innovation

Electricity-based technologies show promise in developing meat products customized to specific health requirements. For example, PEF technology has been demonstrated to facilitate the production of low-salt meat products. It does so by enhancing salt diffusion and perception, thus reducing sodium content without sacrificing flavor or texture[44–45]. This approach is especially relevant for dealing with chronic diseases like hypertension. Additionally, studies on utilizing ES to lower Neu5Gc levels in red meat present a direct strategy for creating healthier red meat products[28].

Through precise adjustment of electric field parameters, ES can promote the release or formation of bioactive compounds, such as bioactive peptides and antioxidants, in meat. This enables the development of functional meat products, including antihypertensive and antioxidant properties[46].

Electricity-based technologies can enhance traditional meat processing methods, such as marinating, fermenting, and drying, by improving efficiency and product quality. For instance, PEF speeds up marination, and its combination with ultrasound enhances water-holding capacity and sensory characteristics. In culinary applications, electric field-assisted thawing (e.g., using HVEF) allows for faster and more uniform thawing, reduces drip loss, and better preserves meat quality and flavor, providing improved pre-processing solutions for both household and foodservice use[47].

4.2 Sustainability and environmental considerations

Compared to conventional thermal processing, numerous electricity-based non-thermal technologies, such as PEF, can achieve comparable results with lower energy consumption and shorter processing durations. Consequently, they reduce carbon emissions and support the food industry's shift towards green and sustainable production[11,48–49].

PEF and UV treatment can effectively inactivate microorganisms, significantly prolonging the shelf life of red meat products and reducing spoilage during storage and transportation. This helps minimize food waste and enhances the overall efficiency of the food supply chain[5,19,48]. Red meat processing by-products are rich in bioactive peptides. In the future, efficient extraction can be achieved using technologies such as PEF, which will further expand the raw material sources of health-oriented products and enhance resource utilization.

4.3 Technology integration and industrialization challenges

Single non-thermal processing technologies often have limitations. For example, PEF has limited penetration in solid meat products, while UV is primarily suitable for surface disinfection. Future development will focus on combining these non-thermal processing technologies with other techniques—such as high-pressure processing, irradiation, or mild thermal treatments like OH—to form comprehensive barrier treatment strategies.

UV and irradiation technology can be used synergistically for sterilization, reducing irradiation intensity and preventing the development of irradiation-induced off-flavors in meat products. Combining PEF with natural antimicrobial agents—such as *Rosa roxburghii* polyphenols—for synergistic sterilization can achieve sterilization while imparting a distinctive flavor to meat products. This integration can overcome the drawbacks of single technologies and achieve more comprehensive microbial control and quality improvement[19,45]. In addition, the experience of quantitative microbial risk assessment in poultry meat[43] can serve as a reference for microbial safety control in red meat non-thermal processing.

Although electricity-based technologies have shown significant promise at the laboratory scale, their industrial application still encounters challenges, including high equipment costs, operational and maintenance expenses, and limited adaptability to large-scale continuous production lines[19,50]. Accelerating the shift to domestically produced alternatives will make the equipment replicable and cost-effective. Small and medium-sized enterprises can outsource the electro-effect processing stage to contract manufacturers that already have non-thermal processing equipment, thereby reducing the cost per batch through economies of scale. Additionally, the introduction of entry-level modular equipment will lower the initial investment threshold.

As these technologies reach maturity, establishing industry-wide standards and regulations will be crucial to ensure product quality, safety, and consistency, thus facilitating wider adoption across the food industry[46].

4.4 Research frontiers and intelligent development

Future research will increasingly utilize advanced modeling, simulation, and artificial intelligence (AI) technologies to analyze and optimize the complex relationships between electric field parameters and meat quality characteristics, and to support the development of meat behavior prediction models tailored to specific processing conditions. Combining sensor technology with automated control systems will enable real-time monitoring and precise regulation of power processing, ensuring that the results remain stable and consistent with AI model predictions. Combined with advanced detection technologies such as proteomics[34,51], the impact of non-thermal processing on the meat proteome can be thoroughly analyzed, offering a more precise molecular basis for parameter optimization[46].

Consumer acceptance is crucial to the market success of novel technologies. Future studies should concentrate on comprehending consumer perceptions, preferences, and trust regarding electricity-processed non-thermal meat products. Transparent communication and consumer education will be essential for enhancing market acceptance[17,52].

5 Conclusion

Physical electrical effect non-thermal processing technologies have achieved remarkable progress in the field of red meat food science, offering innovative solutions to enhance the nutritional, safety, and flavor characteristics of red meat. From ES for accelerated tenderization to PEF, OH and UV radiation for efficient microbial inactivation and quality improvement, these techniques are progressively reshaping the processing landscape of red meat. Research on reducing the levels of Neu5Gc, a carcinogenic precursor in red meat, through ES has added a new dimension to the health attributes of red meat.

Physical electrical effect non-thermal processing technologies will continue to evolve toward diversification, intelligence, and sustainability. Key future research and industrialization priorities will include technological synergy, breakthroughs in industrial-scale production, refined parameter optimization, and enhanced consumer acceptance. By deeply understanding the biochemical, molecular biological, and microbiological mechanisms of these technologies and integrating them with other advanced approaches, we can develop healthier, safer, tastier, and more environmentally friendly red meat products. This will better meet humanity's evolving demands for healthy diets and propel the entire food industry toward a sustainable future.

Conflict of interest

The authors declare no conflict of interests.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (32460600).

Author contributions

Jiangtao Wen: Writing-review & editing (lead), visualization (lead). Li Yang: Conceptualization (lead), writing-review & editing (supporting). Yupan Gao: Methodology (lead), writing-review & editing (supporting). Longfei Chen: Methodology (supporting), writing-review & editing (supporting). Qiujin Zhu: Writing-original draft (lead), funding acquisition (lead), project administration (lead), supervision (lead).

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