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Review Article

Advanced preservation technologies for the safety and quality of meat products

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Abstract

Meat preservation sector has witnessed several technological advancements to ensure enhanced safety and quality to its consumers. The technical progress in preservation with time have always stressed to overcome the undesirable effects of traditional methods. The quest for fresher, nutritious options has spurred innovative approaches aiming to control microorganisms and enzymes without affecting sensory and nutritional properties. Novel techniques include high pressure processing (HPP), preserving food without sensory alterations, pulsed electric field (PEF) technology enhancing mass transfer and ohmic cooking minimizing texture changes. Cold plasma technology ensures food safety without heat, while UV(Ultraviolet) irradiation and natural antimicrobials like essential oils and bacteriocins offer microbial control. Packaging innovations like active and intelligent packaging aid in altering food conditions and quality monitoring. Modified atmosphere packaging (MAP), altering atmospheric air, preserves meat integrity. These methods collectively aim to meet consumer preferences for safe, fresh and minimally processed meat products while extending shelf life and maintaining quality.

Keywords: Advancement, HPP, Meat, PEF, Preservation,

Highlights

- Several advancements have been witnessed in meat preservation industry.
- High pressure processing, pulsed electric field, cold plasma etc. are the latest techniques.
- Advancements in packaging techniques also contribute significantly to preservation.

INTRODUCTION

Advancements in meat preservation techniques have evolved over time to meet consumer demands for safe, high-quality, and minimally processed food products. Traditionally, preservation methods rely on temperature control, humidity regulation, and inhibition processes to prolong shelf life. Techniques such as drying, chilling, freezing, curing, smoking, and canning have long been utilized to preserve meat. However, these traditional methods often result in undesirable alterations in meat properties, including changes in color, flavor, texture and nutritional value. The surge in consumer interest in fresher, nutritious foods has spurred the development of novel preservation approaches that aim to effectively control microorganisms and enzymes without compromising sensory or nutritional attributes (McMillin, 2008).

The emergence of innovative preservation technologies has shown promise in meeting these demands. High-pressure processing (HPP) stands as one such technique, leveraging pressure to inactivate microorganisms and extend shelf life without altering the sensory characteristics of food (Pal & Devrani, 2018). Pulsed electric field (PEF) technology, with its ability to induce changes in cellular membranes and enhance mass transfer, is gaining attention as an efficient preservation method (Barba et al., 2018). Additionally, ohmic cooking, utilizing electrical currents to uniformly and rapidly heat food, has shown potential in preserving meat while minimizing texture alterations (Kumar, 2018). Cold plasma technology, leveraging ionized gas to deactivate microorganisms, presents a nonthermal method for food safety and quality preservation (Umair et al., 2022). UV (ultra violet) irradiation, particularly UV-C light, has been explored for its microbial reduction capabilities on raw meat surfaces, although combining it with other techniques is recommended for complete decontamination (Yang et al., 2017).

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Furthermore, the utilization of natural antimicrobials and bio-preservation strategies, such as essential oils and bacteriocins from lactic acid bacteria, offer promising avenues for extending the shelf life of meat products while addressing consumer preferences for natural preservatives (Yusuf, 2018). Advancements in packaging technologies also contribute significantly to meat preservation. Active packaging, employing additives in polymer materials to alter food conditions and extend storage life and intelligent packaging, incorporating sensors and indicators to monitor and maintain food quality, represent innovative approaches (Lopez-de-Dicastillo et al., 2011). Modified atmosphere packaging (MAP), which involves altering the composition of atmospheric air surrounding the meat, has seen variations using gases like nitrogen and carbon dioxide to maintain meat integrity and appearance. These diverse preservation methods and packaging innovations collectively aim to meet consumer demands for safe, fresh and minimally processed meat products while extending shelf life and maintaining quality.

Recent advancements in meat preservation

Various techniques have been used since ancient times to preserve meat. Drying, chilling, freezing, curing, smoking and canning have long been used to preserve meat. Drying is one of the oldest methods of preserving meat. Heat treatment is the most widely used method to kill microorganisms and impart long-term shelf life to foods. Traditional preservation methods can result in undesirable changes such as loss of color, flavor, texture and nutritional value (Fellows, 2017). Increasing consumer demand for nutritious and "fresh" tasting foods has led to the development of new milder processes and approaches. The main goal of new preservation techniques is to kill or inactivate unwanted microorganisms and enzymes without compromising nutritional or sensory properties. Novel preservation techniques have the potential to meet consumer demand. Here we have discussed some of the new preservation techniques for meat and meat products (Table 1).

High pressure processing: The ability of high pressure to inactivate microorganisms and denature proteins

Table 1. Advanced preservation techniques in meat

Technique	Category	Mechanism of Action	Key Benefits	References
High Pressure Processing (HPP)	Non-Thermal Physical	High hydrostatic pressure (100-800 MPa) denatures microbial proteins and enzymes, leading to microbial inactivation.	Superior sensory and nutritional quality retention compared to heat treatment; effective pathogen control on meat (e.g., *Listeria*); extends refrigerated shelf-life.	Jung & Tonello-Samson (2020).
Pulsed Electric Field (PEF)	Non-Thermal Physical	Applies short, high-voltage pulses that cause electroporation (pore formation) in microbial cell membranes, leading to cell leakage and death.	Minimizes heat damage to nutrients and color; effective against vegetative cells; can enhance meat tenderization and mass transfer (marination).	López-Gómez & Elez-Martínez (2014).
Ohmic Cooking	Thermal Electrical	Internal heat generation through Joule heating (meat resists electric current), providing rapid and exceptionally uniform heating throughout the product.	Fast, uniform heat distribution minimizes overall processing time and thermal abuse; reduces quality degradation (less protein denaturation, lower drip loss in meat).	Gavahian & Khaneghah (2018).
Cold Plasma (CP)	Non-Thermal Gaseous	Generates highly reactive species (Reactive Oxygen/Nitrogen Species, UV photons) that rapidly oxidize and damage microbial cell walls and DNA on surfaces.	Surface decontamination of meat and packaging materials; low-temperature operation preserves heat-sensitive qualities; chemical-free process.	Misra & Jo (2017).

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Technique	Category	Mechanism of Action	Key Benefits	References
UV (Ultraviolet) Irradiation	Non-Thermal Radiation	UV-C light (200-280 nm) damages microbial DNA by causing photohydration of pyrimidine bases, inhibiting replication and growth.	Effective for surface pathogen reduction (e.g., carcass surfaces, processing equipment); low cost; no chemical residues.	Sharma et al. (2023).
Bio-preservation	Biological / Natural	Uses antagonistic microorganisms (e.g., Lactic Acid Bacteria) or their purified antimicrobial metabolites (e.g., bacteriocins) to inhibit spoilage and pathogenic bacteria.	Clean label solution; natural extension of microbial lag phase; can subtly enhance flavor (meat fermentation); improves safety.	Bhattacharya et al. (2022).
MAP / Intelligent Packaging	Barrier / Smart Monitoring	MAP: Controls gas composition to slow microbial growth and oxidation. Intelligent: Uses sensors/indicators for real-time quality assessment; temperature, microbial metabolites etc.	Sustains shelf-life after initial treatment; prevents recontamination; provides quality assurance data to the supply chain and consumer in meat industry.	Heo & Lim (2024).

has been known for over 100 years. High-pressure food processing technology began in the late 19th century and the first application of high-pressure food technology was to sterilize food. It has been discovered that high pressure could be used in the processing of dairy and meat products and that the shelf life of milk could be extended, making it the first time that high pressure can be used as a food processing method. Early successes were achieved with fruit-based products such as orange juice and avocado paste (guacamole). These could be stored for several weeks at the cooling temperature without significant loss of quality after processing at about 500 MPa (Sukmanov et al., 2019).

The use of high-pressure processing in food technology has shown promise in enhancing food safety and quality. By subjecting microorganisms to high pressures, cellular damage occurs, affecting various components like cell membranes, ribosomes and enzymes crucial for their survival. This technology has been effective in reducing the viability and growth rate of bacteria, with Gram-negative types being more susceptible (Ozaybi, 2024). Factors like pressure levels, temperature, and food composition impact the extent of microbial inactivation. High-pressure processing serves as a final step in food production, eliminating pathogens like Salmonella and Listeria without altering taste, color, or texture. Additionally, it extends shelf life, tenderizes meat, improves gel formation in proteins and can enhance the shelf life of cooked meat products prepared conventionally (Pal & Devrani, 2018).

High pressure processing (HPP) in the meat industry relies on both pressure and temperature and they can't be separated. When food undergoes high pressure, it affects its volume and energy. The process involves using horizontal equipment where plastic carriers hold packaged products, loaded into the vessel automatically. The vessel, supported by a yoke, uses unscrewed plugs preferred for their durability and faster operations in larger vessels. Starting with low-pressure water filling, the vessel is pressurized by high-pressure intensifiers. The pressure is maintained for a specified duration before being quickly released. This cycle concludes by returning the vessel to the loading spot, unloading processed batches, and loading the next batch for a new processing cycle (Jung & Tonello-Samson, 2018). This pressure impacts reactions and changes in food molecules, depending on temperature. The Pascaline law and Le Chatelier's principle are key in HPP. Pascaline law says pressure spreads evenly through food, making processing simpler and more energy-efficient. Le Chatelier's principle shows that pressure affects reactions, shifting them towards a compressed state, impacting reaction rates and molecular changes. Another principle, microscopic ordering, shows that higher pressure at a constant temperature organizes molecules more. This pressure and temperature can either work together or against each other in affecting food molecules and reactions. The pressure generation process for HPP doesn't depend on equipment size. There are two methods: direct compression uses vessel closures to create pressure quickly, while indirect compression involves pumps to pressurize fluids in a vessel and is more common in the food industry, especially for solids and thick liquids (Sukmanov et al., 2019).

HPP is done after food is packaged, so it doesn't come into human intervention. The packaged food is put into baskets and placed in a chamber filled with water. Pressure, much stronger than the deepest ocean, is applied uniformly, instantly affecting enzymes and microbes by changing temperatures. This helps the food last longer without changing its taste or nutrients. Every 100 units of pressure increase the food's temperature by 30 degrees, which helps kill microbes and extends the food's shelf life (Daher et al., 2017). High-pressure processing (HPP) has been studied extensively for its ability to extend the shelf life of various meat products. It's particularly useful for ready-to-eat products where proper hygiene during processing, slicing and packaging greatly impacts shelf life. Studies have focused on different meat products like specialty sausages, dry-cured ham and cooked meats (Tem et al., 2021). High pressure, especially at 600 MPa for certain durations and temperatures, effectively eliminated yeasts and enterobacteria in dry-cured and cooked ham, preventing off-flavors and gas production. LAB (lactic acid bacteria) reduction varied across meat types. While lower pressure and longer durations reduced LAB in sliced cooked ham, it had minimal effect on blood sausages. Interestingly, high-pressure treatment didn't always immediately kill microbes but instead led to delayed reduction or regrowth. Factors like food composition, water activity, presence of fats or exudates and pre-cooking steps influenced microbial behaviour after HPP treatments (Guillou et al., 2016).

The major industrial limitations and practical challenges of High Pressure Processing (HPP) are predominantly economic and technical. The high initial capital investment for the specialized, large-scale HPP equipment (often ranging from hundreds of thousands to several million dollars) is a significant barrier, especially for small and medium-sized enterprises (SMEs). Operationally, HPP is a batch process, which inherently limits high-volume continuous throughput compared to traditional continuous methods, though horizontal systems are improving this. Further practical challenges include the inability to inactivate bacterial spores and certain enzymes without combining HPP with heat (High Pressure Thermal Processing or HPTP), and the incompatibility of the technology with certain food types that have high air content or delicate structures, as the pressure collapses their structure.

Pulsed electric field: Pulsed electric field (PEF) is an innovative method for preserving and enhancing food quality. It involves applying short-duration electric field pulses, typically lasting from nanoseconds to milliseconds, with an electric field strength of 0.1–80 kV/cm to food between electrodes or through them. The crucial parameters for PEF processing are the strength of the electric field, treatment temperature and energy delivered. Compared to traditional thermal methods, PEF causes less deterioration in the nutritional and sensory aspects of food (Barba et al., 2018). This non-thermal technique offers several advantages, including lower treatment temperatures, shorter processing times and potential continuous processing, making it highly appealing for food manufacturers. While it has been extensively studied for pasteurizing and sterilizing liquid foods like milk, dairy products and beverages, its application to solid foods, especially meat, has also gained attention (Khan et al., 2017).

Intense electric pulses can induce irreversible changes in cell membranes, leading to increased permeability, improved mass transfer and cellular tissue disruption. This makes PEF a valuable method for food preservation, modification and tissue breakdown. Its commercial application began in the mid-2000s for fruit juice preservation and later expanded to vegetable processing. Current systems in Europe can process up to 5000 liters per hour for juice preservation. PEF technology has diverse applications, including cold pasteurization, enzyme inactivation, extraction of bioactive compounds, reducing allergenicity, lowering contaminants, food dehydration and freezing processes. High-intensity PEF, despite being generally non-thermal, has the potential to create heat, which might impact the quality of solid foods such as fresh meat by causing a cooking-like effect (Bekhit et al., 2017). In the absence of an external electric field, cells naturally possess a transmembrane potential. When an external electric field is applied during PEF processing, it triggers the movement of ions inside and outside the cells, leading to the accumulation of ions on cell membranes and cell polarization. This accumulation results in a reduction in membrane thickness due to electro-compressive forces, leading to the creation of pores in the membrane, a process known as electroporation. There are two main theories explaining electroporation: one involving the breakdown of the membrane due to electro-compressive forces and the other focused on the transformation of hydrophobic pores into hydrophilic ones. Both theories highlight the increase in membrane permeability due to the formation of pores under the influence of PEF (Toepfl et al., 2014).

The critical electric field strength needed for electroporation to occur depends on various factors, including food properties (liquid, viscoelastic, or solid), process parameters (temperature, pulse duration, amplitude and number of pulses), cell characteristics (type, size, shape) and membrane properties (ionic strength, thickness, structure). The intensity of the electric field must exceed a critical threshold for electroporation and this critical value varies for different cells-ranging from 1–2 kV/cm for plant cells to 10–14 kV/cm for microbial cells (Buckow et al., 2014). For microbial inactivation, high electric field strengths (10–40 kV/cm) and energy input are required, whereas lower field strengths (1–10 kV/cm) are sufficient for structural changes or tenderization in animal or plant tissues. However, intense PEF treatments (above 10 kV/cm) on fresh meat might induce cooking effects on the meat edges (Bekhit et al., 2014).

There's a scarcity of research on PEF's application in solid foods like meat, although it's recognized as a promising area, particularly for industrial use (O'Dowd et al., 2013). Some studies pointed to PEF's ability to improve meat quality by enhancing mass transfer during drying and brining, resulting in better water binding during cooking (Mok et al., 2017). Recent research has focused on meat safety, tenderization, supercooling and accelerated brining using PEF. The method has shown potential to alter various meat quality traits like texture, color and water-holding capacity while improving curing and brining processes (Mustafa et al, 2025). PEF treatment may cause a mild temperature increase, impacting meat quality and when combined with ohmic heating, might affect muscle cell membranes and consequently, meat quality (McDonnell et al., 2014). Studies investigating PEF's impact on the flavor profile and sensory attributes of cooked lamb noted changes in flavor attributes, associating treated samples with positive qualities like meaty, juicy and browned flavours (Ma et al., 2016).

The commercial adoption of Pulsed Electric Field (PEF) in the meat industry faces several industrial limitations and practical challenges, primarily stemming from high initial capital investment for the specialized, high-voltage equipment and electrode-food interactions. Specifically, the batch nature of solid food processing, the heterogeneous composition of meat (varying fat, bone, and connective tissue) that complicates uniform field distribution, and the potential for electrochemical reactions at the electrode interface leading to corrosion, fouling, and the migration of metallic ions into the product (affecting taste and safety) are major hurdles. Furthermore, while PEF effectively aids tenderization and mass transfer (e.g., marination), its limited efficacy against bacterial spores and some enzymes necessitates combination with other methods, and there are still controversial or inconsistent results in the literature regarding its precise effects on meat quality attributes like cooking loss, color, and long-term sensory properties.

Ohmic cooking: The conventional methods of heating food often result in uneven treatment, affecting both texture and microbial quality. To address these limitations, the emerging ohmic heating technique has gained attention as an alternative means of uniform and rapid heating without compromising food quality. Ohmic heating, also known as joule or electrical resistance heating, involves passing an electric current through food, generating internal heat due to its natural electrical resistance. This method ensures swift and consistent heating, preserving food quality and safety. Ohmic heating finds applications across various food processing stages like evaporation, cooking, pasteurization, and sterilization, among others, proving advantageous in minimizing thermal damage to essential components like pigments and vitamins. Unlike traditional methods, ohmic heating allows for achieving higher temperatures in solid foods without concerns about burning or fouling, making it applicable to a wide range of food products (Kumar, 2018). Ohmic heating, also known as Joule heating due to its association with electric current producing heat, traces its origins back to 1897. The method gained attention in the late 1920s as a commercial method known as the "Electro-Pure" method, notably used for electric pasteurization of milk and other fluids. By the early 20th century, it was extensively applied, including for blanching to prevent enzymatic discoloration of potatoes. However, due to issues with controls and electrode materials, interest in this technique waned, except for its use in electroconductive thawing. Recent years have seen renewed interest and attempts to utilize ohmic heating in various food processing applications. The first commercial application of ohmic heating to sterilize particulate foods was developed by APV Baker Ltd, (Skudder, 1992).

Ohmic heating operates on the principle of electrical conductivity within solutions containing electrolytes, commonly found in foods with high water content. In this process, when an electric field is applied to these solutions, ions within the electrolyte move toward oppositely charged electrodes, generating heat due to their movement. Collisions between ions increase resistance, elevating their kinetic energy and consequently heating the material. An ohmic heater uses this electrical resistance within a liquid to generate heat through Joule heating, produced by an alternating electric current passing through a conductive material with resistance, resulting in a temperature increase within the fluid. Ohmic heating offers several advantages, including low maintenance costs, efficient heating of particulate foods and mixtures, rapid temperature attainment, uniform and quick heating rates, enhanced product quality and energy efficiency. It enables high efficacy, immediate device shutdown, minimal heat transfers after shutdown and an eco-friendly, low-fouling system. This method preserves food color and nutritional value, minimizes processing time and ensures high yield. (Jan et al., 2021).

Ohmic heating, an expedient cooking method for meat, leverages electrical energy to rapidly generate heat within the meat. Studies on pork, chicken and beef cuts utilizing ohmic heating revealed differences in conductivity between lean and fat portions (Zell et al., 2009). Lean portions have a higher electrical conductivity than fat portions. This difference is significant for ohmic processing as the high conductivity of lean meat allows for more rapid heating compared to fatty cuts. The non-linear relationship between fat content and conductivity means that adding fat reduces overall conductivity. While color attributes in meat remain unaffected by initial fat content or voltage gradients during beef cooking with ohmic heat, the process does induce a significant white color in comparison to conventional cooking. Beyond color, ohmic heating affects meat texture by denaturing proteins and inducing structural changes, including cell membrane destruction, muscle fiber shrinkage, connective tissue solubilization and protein gel formation. Ohmic thawing has been noted to preserve proteins and reduce fat globule removal compared to conventional methods, although it can toughen collagen and beef muscles (Icier et al., 2010).

The application of ohmic cooking in the meat industry faces significant practical and industrial challenges, primarily due to the heterogeneous electrical conductivity of meat products; non-conductive components like fat, bone, and connective tissue create areas of high electrical resistance, resulting in cold spots (under-processed regions) and hot spots (over-processed regions) that compromise both food safety (microbial inactivation) and product quality (uneven cooking, altered texture). Additionally, the use of electrodes in direct contact with the meat can lead to electrochemical reactions, causing electrode corrosion, fouling, and the migration of metallic ions into the food, which raises food safety concerns and may negatively impact sensory properties like taste and color, ultimately hindering reliable large-scale industrial adoption (dos Santos et al., 2024).

Cold plasma technology: Plasma technology has emerged as a nonthermal method, originally used in polymer bonding but now applied to food processing. This approach utilizes ionized gas to deactivate microorganisms, including bacteria, spores, and viruses. Plasma technology offers advantages like environmental safety, minimal generation of hazardous substances, and sterile, reproducible processes. However, challenges such as installation costs, specific equipment needs, security measures and the requirement for trained personnel exist. Understanding plasma's impact on food components, enzyme degradation and sanitation in processing equipment is crucial (Umair et al., 2022).

The sterilization potential of plasma was first acknowledged in 1960 and patented in 1968. Termed as "cold" due to its operation at room temperature, cold plasma comprises partially ionized gas containing various reactive species like ions, radicals, photons and reactive oxygen and nitrogen species (Stoica et al., 2014). Cold plasma (CP) technology is increasingly applied in food safety and sterilization, offering non destructive disinfection methods for air, water and surfaces. There are two types: low-pressure plasma and atmospheric-pressure plasma. Low-pressure plasma operates in vacuum conditions or low pressures, while atmospheric-pressure plasma operates at radio-frequency, ionizing gases using electrical stimulation. CP's low temperature makes it cost-effective and suitable for the food industry.

Indirect CP, known as "afterglow," is used for packaged food, preventing post-packaging contamination without penetrating the food. CP does not permeate the food but alters its surface. It's eco-friendly, sterilizes cleaning materials and deactivates harmful bacteria without environmental harm. Vacuum ultraviolet radiation and reactive oxygen species produced in the plasma effectively detach and sterilize contaminants on surfaces. CP generates reactive oxygen species that neutralize bacteria, making it effective in decontamination. This process creates minimal harmful gases and doesn't significantly impact the environment. CP's advantages lie in its ability to neutralize various microorganisms and bacterial spores. It interacts with microbial cells through oxidative effects, damaging DNA through the formation of reactive oxygen species like hydroxyl radicals and hydrogen peroxide. This oxidative damage affects microbial DNA and cell structures (Pankaj et al., 2014).

Cold plasma (CP) treatment offers numerous advantages in food processing, such as environmentally friendly decontamination, low energy use and rapid microorganism inhibition on surfaces without leaving residues. However, its application in high-fat foods may lead to increased production of reactive oxygen species (ROS), resulting in lipid oxidation, which can compromise food quality, cause nutrient loss and alter sensory properties. To mitigate lipid oxidation, modified gas mixtures or vacuum packaging can help reduce oxygen levels and prevent oxidative rancidity in food products (Natpaphan et al., 2024). Optimizing process parameters like input power, gas composition and temperature can also minimize lipid oxidation. CP treatment might affect water holding capacity in fish fillets, leading to water leaks during storage (Ucar et al., 2021). The impact of cold plasma treatment on meat and its products is multi-faceted, especially concerning colour, pH, lipids and microbial quality. Colour enhancement, a vital factor for consumer perception, has been achieved through plasma treatments, affecting traits like redness, lightness and yellowness in various meats. pH alterations post-treatment varies, with some meats exhibiting decreased pH due to plasma-induced acid formation, impacting freshness and meat quality. Lipid oxidation, influenced by reactive oxygen species in plasma, shows mixed results across studies, with some meats being more resistant to oxidation than others. Microbial quality demonstrates potential improvement through plasma treatments, reducing bacteria like *E. coli*, Salmonella and *L. monocytogenes* in different meats, thereby potentially extending shelf life (Akhtar et al., 2022).

The limitations and practical challenges of cold plasma technology in the meat industry focuses on its potential to degrade meat quality and the difficulties in commercial scale-up. Specifically, the reactive species generated by cold plasma can accelerate lipid oxidation in fat-rich meat products, leading to off-flavors, rancidity, and undesirable changes in color (e.g., reduced redness), which negatively impacts consumer acceptability; furthermore, current cold plasma systems offer limited penetration depth, making them most effective only for surface decontamination, and commercialization is hampered by the need for process standardization across different meat cuts and processing lines, high initial equipment costs, and the technical hurdle of engineering high-throughput, uniform treatment systems for large volumes of product.

UV (Ultra Violet)-C irradiation: UV-C light (200-280 nm), falling within the ultraviolet spectrum, has immense potential in sterilizing surfaces, indoor air and liquids, yet its utilization in the food industry remains limited. Germicidal Ultraviolet UV-C technology in meat processing facilities boosts profits by enhancing sanitation. Its effective disinfection leads to safer work environments, better product quality, extended shelf life, and increased profitability. UV-C is both cost-effective and quick, making it an ideal method for disinfection (Atlantic Ultraviolet Corporation [AUC], 1963). When applied, UV-C light induces the generation of photoproducts like pyrimidine pyrimidone (6–4) and pyrimidine dimers, causing damage to the DNA and proteins within microbial cells. This damage disrupts DNA transcription and replication by altering the hydrogen bonds between nucleobases, resulting in impaired repair processes, mutations and ultimately, cell death (Rastogi et al., 2014).

Regarding raw meat decontamination, research groups have explored the potential of UV-C LEDs in reducing microbial loads. For instance, on pork, doses up to 2040 mJ/cm^2 resulted in reductions of 0.56, 0.82 and 0.95 log for *Yersinia enterocolitica* after 1, 7 and 14 days of storage, respectively (Reichel et al., 2019). Similarly, doses of 1 J/cm^2 demonstrated notable reductions for *Yersinia pestis* on chicken breast filets and beef steaks (Sommers & Sheen, 2015). Additional studies have shown significant reductions for *Salmonella Enteritidis*, *Listeria monocytogenes, Staphylococcus aureus* and enterohaemorrhagic *Escherichia coli* when chicken filets were irradiated with doses up to 3 J/cm^2 at a distance of 6 cm (McLeod et al., 2018). Combined treatments have also been explored to enhance microbial reductions on raw meat. One study, combining UV-C treatment at 590 mJ/cm^2 with gaseous ozone, significantly reduced pathogens on fresh beef (Kalchayanand et al., 2020). Similarly, synergistic treatment of *Listeria monocytogenes* with UV-C light and phage on chicken breast resulted in substantial reductions (Yang et al., 2017). However, certain combined treatments, like chlorine and UV-C, showed limited effectiveness in reducing *Listeria monocytogenes* on chicken meat (Oh et al., 2014). Assessment of UV-C irradiation impact on the organoleptic properties of raw meat, such as color and texture, indicated minimal to no influence on the treated samples. Although UV-C radiation aids in reducing surface microbes on meat, it's insufficient for complete elimination. Therefore, combining this method with other decontamination technologies is recommended to bolster the microbial safety of raw meat (Kalchayanand et al., 2020).

The industrial application of UV-C irradiation in the meat industry is significantly limited by its poor penetration depth, meaning it's primarily effective for surface decontamination and struggles to inactivate microbes harbored in meat crevices, rough surfaces, or deeper tissues, thereby limiting its overall log reduction capability. Practical challenges include ensuring a uniform UV dose across irregular or complex meat surfaces, as shadowing from surface irregularities, blood, or other organic matter can shield microorganisms and reduce efficacy; furthermore, excessive UV-C exposure can lead to the formation of free radicals, potentially accelerating lipid oxidation and causing undesirable changes like slight discoloration or a burnt odor in the meat, necessitating precise process control and careful integration into existing high-throughput processing lines.

Natural antimicrobials and biopreservation: Biopreservation is the utilization of natural antimicrobial agents or controlled microflora to extend the shelf life and enhance the safety of food products. Consumers widely accept phytochemicals over synthetic preservatives, making them an attractive alternative. For biopreservatives used in meat products, efficacy, safety, stability, and cost-effectiveness are key factors (Galvez et al., 2008). Various spices and essential oils are known for their preservative properties and have been employed to prolong the storage life of meat products. For instance, the aqueous extract of garlic exhibited inhibitory effects against various microbial contaminants on poultry carcasses in refrigerated conditions, attributing its efficacy to allicin, the primary antimicrobial component (Oliveira et al., 2005). Essential oils (EOs) are plant-derived volatile and aromatic extracts with diverse biological effects like antibacterial, anti-inflammatory, and antioxidant properties (Rout et al., 2022). Essential oils, containing compounds like thymol, eugenol, carvacrol and trans-cinnamaldehyde, have demonstrated antimicrobial properties mainly against Gram-positive bacteria by disrupting cellular membranes, electron flow and active transport (Lambert et al., 2001).

The use of lactic acid bacteria (LAB) and their metabolites as natural preservatives in food products offers multiple advantages. These substances effectively combat pathogens by disrupting cell membranes and are considered a promising solution to address microbial resistance to antibiotics. Incorporating LAB-derived active peptides directly into product formulations during processing or introducing live cultures as part of fermentation practices in the meat processing industry are common strategies. Additionally, antimicrobial active packaging, through adsorption or coatings, involving LAB metabolites like bacteriocins and organic acids, actively reduces the growth of spoilage microorganisms in foods (Liu et al., 2022). The biopreservation and the use of both bacteriocins produced by lactic acid bacteria (LAB) and bacteriocinogenic strains as an alternative to substitute chemical antimicrobials for food preservation became increasingly important in the last two decades (Acuña et al., 2011). Furthermore, bacteriocin-producing LAB strains demonstrate probiotic potential, offering health benefits by suppressing enteropathogenic bacteria in the gastrointestinal tract. Recent research has unveiled novel bacteriocins from different LAB strains, showcasing their potential as biopreservatives in various food systems. These novel compounds exhibit significant inhibition of pathogens and maintain the quality attributes of meat products during storage. For instance, bacteriocins extracted from specific LAB strains have displayed strong inhibitory effects against major foodborne pathogens like *L. monocytogenes, S. aureus* and *E. coli* in diverse food matrices, suggesting their potential for food preservation (Lu et al., 2020).

Nisin, a polycyclic antibacterial peptide derived from *Lactococcus lactis*, is widely used in food preservation. With 34 amino acid residues, including unique components like lanthionine, methyllanthionine and didehydroalanine, nisin is produced through the fermentation of nisin-producing *L. lactis* strains in a modified environment. It's highly effective against various Gram-positive bacteria by disrupting their cell membrane function. This potent antimicrobial agent shows promise in controlling bacterial growth in poultry, orange juice, fermented meats and dairy products. Nisin has been employed with success against specific bacteria, such as *Listeria monocytogenes*, *E. coli, Pseudomonas aeruginosa* and *Salmonella Typhimurium*, even at lower concentrations in diverse food systems. Its combination with other compounds like EDTA or essential oils, such as oregano oil, amplifies its antimicrobial activity. Nisin, alone or combined with other natural compounds, inhibits fungal growth and extends the shelf life of various food products. Encapsulation methods have been employed to improve its effectiveness against specific bacteria under varied environmental conditions (Yusuf, 2018). Combination of nisin and acetic acid was the most effective organic acid treatment against *L. monocytogenes,* with a 6.00 Log_{10} CFU/cm^2 reductions on sliced cooked pork bologna at 4°C for 120 days (Samelis et al, 2005). Similarly, the use of combination of nisin and EDTA has the strongest inhibitory effect which reduced the *L. monocytogenes* population to 1.99 Log_{10} CFU/g on turkey ham at 4°C during 63 days of storage (Ruiz et al, 2009).

The primary industrial limitations and practical challenges of employing natural antimicrobials and biopreservation in the meat industry revolve around efficacy, stability, and sensory impact at a large scale. Natural compounds like plant extracts or essential oils often exhibit a narrow antimicrobial spectrum and are prone to degradation due to processing conditions (like heat) or interactions with the complex meat matrix (proteins and fats), leading to inconsistent or insufficient microbial inactivation compared to traditional chemical additives. Furthermore, achieving an economically viable and consistent supply of high-purity natural antimicrobials is a scale-up hurdle, while the often-intense flavor and aroma of many effective plant-based compounds can negatively impact the sensory quality and consumer acceptance of the final meat product.

Novel packaging technology

Active packaging: Active packaging is a natural, recyclable and biodegradable packaging material developed to meet consumer demand for natural, recyclable and biodegradable materials. It prolongs storage life and enhances food safety by altering food conditions. Active packaging is used as a substitute for conventional food processing techniques, such as high thermal treatments, brining, acidification, dehydration and additive preservation (Lopez-de-Dicastillo et al., 2011). The use of active packaging depends on the incorporation of specific components inside the polymer and the intrinsic characteristics of the polymer used as packaging vehicle.

Active packaging falls into two categories: absorbers and emitters. Absorbers eliminate unwanted elements like moisture, oxygen, carbon dioxide, ethylene, and UV light from food or its environment. Emitters, on the other hand, introduce substances like antimicrobials, antioxidants, flavors, and even carbon dioxide to the packaged food or its surrounding space (Fadiji et al., 2023). A new advancement in active packaging is the addition of polymer materials containing additives that impart antimicrobial properties (Suppakul et al., 2003). These polymeric matrices can release active agents, retaining compounds, or undesirable food components. Controlled delivery of active agents into food via packaging films for extended storage and distribution restricts the development of undesirable flavors (Flores et al., 2007). Artificial antioxidative agents like butylated hydroxytoluene, thioester and organophosphate compounds are limited due to toxicity (Gómez-Estaca et al., 2014). In active packaging systems, choosing an antioxidant is critical and the choice should be compatible with the packaging material and form homogenous distribution to the food or package headspace. Antimicrobial agents can be used to decrease or inhibit microbial growth in food packed or within food packages. Moisture controlling agents like natural clays, calcium oxide and silica gel are used as desiccants for dry foods and internal humidity regulators for high moisture content foods (Falguera et al., 2011).

Intelligent packaging: Intelligent packaging is a technology that aims to enhance food quality characteristics and safety by intentionally combining food with its packaging or surroundings. A recent report on Smart Packaging highlights its capability to monitor a product from production to consumption. It enables analysis and regulation of the package's internal or external environment, providing real-time information to manufacturers, retailers, or consumers about the product's status at any point in time (Blue Bite, 2023). It is linked to advancements in time-temperature regulators, ripeness monitors, biosensors and radio frequency indicators. Intelligent packaging provides information about the enclosed food and its environment, helping retailers, customers and manufacturers understand its properties (Restuccia et al., 2010). It also monitors internal and external conditions, assessing the quality of the food product directly within the package. Indicators used in intelligent packaging include gas leakage, ripeness regulators, time-temperature monitors, bioprobes, radio frequency indicators and toxin indicators. It also uses self-heating and cooling systems as temperature regulators, ethylene adsorbers and absorbers to maintain food quality. Radio frequency identification (RFID) is used in intelligent packaging to wirelessly track items, enhancing food safety and supply chain effectiveness. This technology has also played a role in nanotechnology, resulting in quality and safety monitoring and sustainability of packaging (Yam et al., 2005).

Modified atmosphere packaging (MAP): Modified atmosphere packaging (MAP) for meat relies on packaging materials that prevent moisture and gas from permeating, ensuring a consistent environment during storage. It involves altering the usual composition of atmospheric air and encompasses both aerobic and anaerobic packaging for meat. Dry air at sea level mainly consists of nitrogen (78%), oxygen (20.99%), argon (0.94%) and a trace of carbon dioxide (0.03%), though these proportions vary by weight. While low oxygen MAP is available and cost-effective, it's less commonly used; primarily due to consumer preference for the bright red colour of fresh meat (which requires high oxygen) and the potential food safety risks associated with anaerobic bacterial growth if temperature is not strictly controlled. Innovations like shrinkable film on form-fill-seal equipment minimize film use and wrinkles (McMillin, 2008). Low oxygen MAP utilizes an anoxic atmosphere of nitrogen and carbon dioxide wherein, Nitrogen, an inert gas, maintains package integrity without reacting with meat pigments, while carbon dioxide interacts with meat, influencing its properties. Barrier trays, filled with product and flushed with the desired gas mix, are sealed with barrier lidding film. These trays, usually preformed off-site or created on form-fill-seal equipment, maintain meat pigment in a deoxymyoglobin state, appearing purple, which might be unappealing to consumers (Eilert, 2005).

Non-barrier overwrapped meat packages can be enclosed in appropriately sized barrier pouches or larger barrier film master packs containing multiple packages in an anoxic gas. When removed for retail display, the meat pigments become oxygenated. An alternate method involves anoxic MAP using an inner air-permeable film and an outer barrier film. Peeling off the outer film exposes the meat to atmospheric oxygen, causing it to bloom. Microperforated shrink films with additional holes promote faster blooming after removing barrier film or overwrapped trays from master packs (McMillin et al., 1999). Carbon monoxide (CO) has been used in low oxygen retail packaging systems. Meat may be exposed to CO before packaging or used in gas flushing, imparting the desired red meat color. Most MAP for fresh meat involves a high oxygen environment (around 80% O_2), offering adequate shelf life for processors and retailers with controlled distribution systems (Belcher, 2006).

Conclusion

Advancements in meat preservation techniques have evolved over time to meet consumer demands for safe, high-quality and minimally processed food products. It is the age of technology where food handling is driven on the latest techniques to enhance the keeping quality and a safety of product. The latest techniques have advantage in maintaining the sensorial and nutritional features and ensuring an appreciable shelf life with least changes in product characteristics. Recent techniques like high pressure processing (HPP), pulsed electric field (PEF) technology, ohmic cooking, cold plasma technology, UV irradiation and natural antimicrobials strategies are all promising avenues for extending the shelf life of meat products. Although these techniques are machine intensive and some other limitations which need to be overcome with future research for the convenience and their applicability in practice.

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