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Review Article

Natural alternatives and innovative approaches to reduce nitrite level in processed meat: A review

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Abstract

Nitrites are one of the multifunctional additives used in meat products. Given that they have high performance such as color creation, flavor improvement, and antioxidant and antimicrobial properties, they have caused consumer concern due to the formation of N-nitroso compounds and related health risks. Consumers demand natural or low-nitrite meat products. Synthetic nitrites are widely used because of their cheapness and easy access. However, due to the formation of nitrosamines, researchers are looking for a safer alternative to this additive. Plants, due to their nitrate content, can be used as natural nitrite sources by nitrate-reducing bacteria. Also, emerging non-thermal technologies such as atmospheric non-thermal plasma and pulsed electric fields can have the potential to be considered as new approaches for nitrite reduction. However, challenges regarding the stability of their sensory properties and antimicrobial efficacy remain. This review systematically evaluates the multifunctional role of nitrites, their health-related implications and potential substitution strategies, and addresses safe, effective, and acceptable solutions for producing high-quality meat and processed products with natural ingredients with a nitrite reduction approach.

Keywords: Meat products, Non-thermal technologies, N-nitroso compounds, Nitrite, Plants.

Introduction

Since ancient times, meat processing has been an effective method for increasing the shelf life of meat products (Alvarado & McKee, 2007). Compounds such as sodium chloride, phosphates, spices, and especially nitrites are added to meat products to improve sensory characteristics and increase safety (Patarata et al., 2020). In the meat industry, sodium nitrite and potassium nitrite have been the most widely used due to their cheapness and easy access (Gassara et al., 2016). Nitrite performs four important functions, such as providing a distinctive, stable red color, creating a special cured flavor, inhibiting lipid oxidation, and providing antimicrobial properties in meat processing (Shakil et al., 2022). Therefore, nitrite is considered a multifunctional and essential compound in meat products.

The concentration of nitrite consumed in cured meats is less than 150 ppm, which has bacteriostatic and bactericidal effects against important pathogens such as *Salmonella enterica serovar* Typhimurium, *Listeria monocytogenes* and *Clostridium botulinum* (Hospital et al., 2014). The effectiveness of the

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antimicrobial property of nitrite depends on several factors including pH, temperature, nitrite concentration, presence of curing accelerators (e.g., sodium chloride, ascorbate, erythorbate), iron level and initial microbial load (Majou & Christieans, 2018). Although nitrite has many technological advantages, it has raised several health concerns among consumers. Nitrite can react with secondary and tertiary amines to form nitrosamine compounds, which are known carcinogens and have been shown to cause gastrointestinal cancers (Oliveira et al., 2004). Toxicologically, nitrite is significantly more toxic than nitrate and has been shown to have a lower lethal oral dose (Shakil et al., 2022).

In light of these issues, regulatory authorities worldwide have imposed strict limits on nitrite use, and dietary guidelines increasingly recommend reducing processed meat consumption (Shakil et al., 2022). Consequently, the Joint FAO/WHO Expert Committee on Food Additives (JECFA) has established an acceptable daily intake of 0.07 mg/kg body weight for nitrite, while generally safe for healthy adults, this level may pose risks for vulnerable populations such as infants and children (Casoni et al., 2019). However, given the high nutritional value of these products as a source of iron, it is not logical to completely eliminate them from the human diet (Hamad & Singh, 2025). Therefore, instead of eliminating the product itself, researchers are looking for a solution to reduce or replace nitrite in the formulation of these products. Recent researches have shown that the use of natural alternatives such as plants, vegetables, and non-thermal technologies can be effective.

Vegetables such as celery, beetroot, and spinach have been used as natural compounds due to their high nitrate content (Majou & Christieans, 2018). Vegetables are an important dietary source of nitrate, which can be converted endogenously in the body to nitrite and nitric oxide (NO) (dos Santos Baião et al., 2021). In addition, plant extracts containing bioactive compounds (e.g., polyphenols and flavonoids) are beneficial due to their antioxidant and antimicrobial properties (Munekata et al., 2020). Essential oils (EOs) have also been investigated for reducing nitrite in cured meats, in a review study, a total of 4850 studies were screened, and 26 studies were included in this review. Cooked-emulsified sausages had 20 ppm cinnamon EO + 100 ppm nitrite, which reduced lipid oxidation by 166%, maintained color, taste, aroma, and overall acceptability compared to the control (120 ppm nitrite) (Corrêa Cardoso et al., 2025).

The use of technological approaches, including high hydrostatic pressure (HHP) (Alahakoon et al., 2015), active packaging (Shiravani et al., 2024), and atmospheric non-thermal plasma (ANP) treatments (Jo, Lee, Lee, et al., 2020) to produce nitrite from vegetables, as well as to reduce the nitrite dosage and improve the color, chemical and microbial properties in meat products, has also been expanded. However, no single, cost-effective alternative has yet been able to cover all the multiple functions of nitrite in meat products, but the combined use of plant-based compounds along with advanced technologies in meat products has been shown to be effective (Alahakoon et al., 2015). Considering the growing consumer demand for healthier, safer, and clean-label products, reformulating meat products with reduced reliance on chemical nitrites has become inevitable (Jayasena & Jo, 2013). Therefore, this review aims to comprehensively examine the functions and associated risks of nitrite in meat products, evaluate emerging natural and technological alternatives, and highlight future challenges and opportunities in the development of healthier meat formulations.

Meat and meat products spoilage and preservation strategies

Meat and meat products are one of the most important groups of prepared foods to provide the body with protein. Sausages are among the most popular meat products that are popular with many consumers around the world (Sampaio et al., 2004). The main ingredients of these products include meat, fat or oil, water, protein binders, fillers, spices, preservatives and other additives (Pereira et al., 2000). Due to the use of numerous spices and additives, the possibility of contamination of these products is higher compared to raw meat; therefore, the use of modern food preservation methods, in addition to conventional storage and packaging, is of particular importance to control the growth of pathogenic and spoilage microorganisms (Del Valle et al., 2002). Furthermore, the grinding process causes damage to muscle cell membranes and accelerates oxidation, affecting four main characteristics of meat products: color, water holding capacity, flavor, and texture (Suman et al., 2016). Also, meat products are subject to significant microbial contamination at various stages of production, processing, and distribution, highlighting the need for effective strategies to prevent spoilage. Specifically, foodborne pathogens including bacteria (e.g., *L. monocytogenes, E. coli, Campylobacter, Salmonella spp., staphylococcus aureus, and Vibrio spp.*), fungi (*Aspergillus fischeri and Byssochlamys fulva/nivea*), parasites (*Toxoplasma gondii, Trichinella spp., Cryptosporidium spp.,* and *Giardia duodenalis*), and viruses (hepatitis A and E, and Norovirus) have been identified at various stages of the production and distribution chain (Bintsis, 2017; Martinović et al., 2016). In addition, factors such as slaughter line, storage temperature, and shelf life are also important risk factors for contamination of meat products (Dimitrakopoulou & Vantarakis, 2022). A major challenge in factory environments is the formation of microbial biofilms on food contact surfaces, equipment, and processing lines (Carrascosa et al., 2021). Biofilms, by creating a sticky and protective structure, allow microorganisms to resist routine washing and disinfection operations and act as permanent reservoirs of contamination. In the meat processing industry, biofilms containing *L. monocytogenes* and other pathogenic bacteria can lead to repeated contamination of finished products and make spoilage control difficult (Dawan et al., 2025). Studies have shown that specific points in production lines have been identified as "microbial niches" and sites of biofilm formation, which are the main source of *L. monocytogenes* contamination (Lüth et al., 2020). Therefore, understanding the processes of microbial spoilage and biofilm formation, and adopting appropriate strategies to prevent the growth and persistence of these agents, is a fundamental step towards maintaining the safety and increasing the shelf life of meat products (Oliulla et al., 2024). According to European Union (EU) regulations, the maximum permitted nitrite content in the form of $NaNO_2$ or $NaNO_3$ is 150 mg/kg of product, but this is reduced to 80 mg in heated products and to 45 mg at the consumption stage. In general, the permitted nitrite content in meat products varies according to different national regulations, for example Denmark applies a stricter limit of 60 mg/kg (Stamenić et al., 2024). Although nitrites are added to most cured meat products to inhibit the growth and production of toxin by *Clostridium botulinum*, the amount required for this antimicrobial effect varies from product to product (Govari & Pexara, 2015). According to the Scientific Committee on Food of the European Food Safety Authority (EFSA), 50 to 100 mg nitrite per kg of meat may be sufficient for most cured meat products. However, for other meat products, especially those with low NaCl content and long shelf life, higher levels of nitrite, as high as 150 mg/kg, are required for effectiveness against *C. botulinum* (Mortensen et al., 2017). As nitrite levels increase, inhibition of *C. botulinum* growth also increases (Sofos et al., 1979). The level of nitrite required to produce color (approximately 25 ppm or less) is very low compared to the level required to control *C. botulinum* in cured meat (Sofos et al., 1979). Nitrates have no direct activity against *C. botulinum* and have stronger antimicrobial activity against Gram-positive bacteria than Gram-negative bacteria. However, the antimicrobial effect of nitrites against Gram-negative bacteria is also significant.

Mechanisms of nitrite and NO-based preservation

Peroxynitrite ($ONOO^-$) is one of the most important reactive nitrogen species (RNS) in both biological and food systems (**Figure 1**)(Majou & Christieans, 2018). It is generated through the rapid reaction of nitric oxide ($NO\bullet$) with superoxide ($O_2\bullet^-$) and functions as a strong oxidant that plays a crucial role in the antimicrobial effects observed in processed meat products (Prolo et al., 2014). With a pKa of approximately 6.8, peroxynitrite exists in two forms at near-physiological pH: the more stable ionic form ($ONOO^-$) and its protonated acid (ONOOH), which can easily permeate biological membranes. At pH values below 7, more than 90% of ONOOH undergoes isomerization to nitrate (NO_3^-), while a smaller fraction decomposes to generate highly reactive hydroxyl ($OH\bullet$) and nitrogen dioxide ($NO_2\bullet$) radicals (Majou & Christieans, 2018). Metmyoglobin ($MbFe^{3+}$) can catalyze this isomerization process, thereby influencing the stability and reactivity of peroxynitrite within meat systems (Herold & Shivashankar, 2003). Peroxynitrite can be formed through two main pathways, the primary route involves the direct reaction between $NO^{\bullet}$ and $O_2{\bullet}^-$, whereas an alternative pathway occurs through the reaction of nitrite (NO_2^-) with hydrogen peroxide (H_2O_2) (Radi, 2013). These two pathways may occur simultaneously in biological tissues and food matrices, leading to the *in situ* generation of peroxynitrite during meat processing. Both $ONOO^-$ and ONOOH are able to cross cellular membranes either through anion channels or passive diffusion. The permeability coefficient of ONOOH (~8×10^{-4} cm/s) is approximately 400 times higher than that of superoxide, allowing this species to act as a highly diffusible and potent oxidant within complex food environments (Su & Groves, 2010).

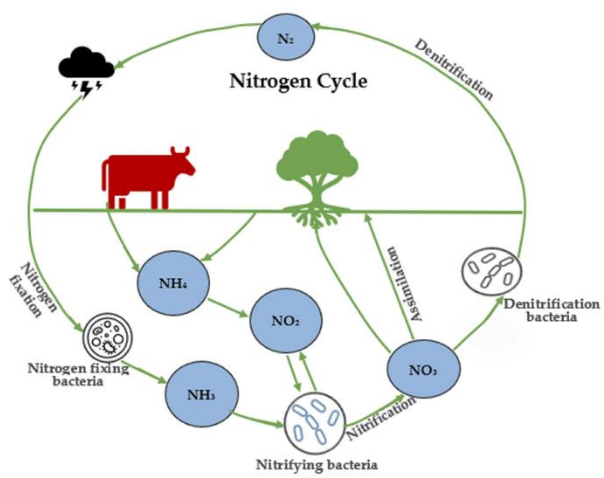

Figure 1. Nitrogen cycle in the environment including nitrogen assimilation form (Shakil et al., 2022).

Once formed, peroxynitrite exerts its bactericidal activity through a combination of oxidative and nitrative mechanisms. It can oxidize essential bacterial proteins, leading to the inactivation of key metabolic enzymes, and nitrate tyrosine residues as well as other susceptible amino acids, altering protein structure and function (Brown & Borutaite, 2006). It is also capable of damaging bacterial DNA through strand breaks and base modifications, while simultaneously inducing lipid peroxidation in cell membranes, which disrupts membrane integrity and permeability. These multiple effects occur simultaneously and synergistically, ultimately leading to the inhibition of bacterial growth or cell death (Ferrer-Sueta & Radi, 2009).

Natural alternatives to nitrite

Artificial nitrites, such as sodium and potassium nitrite, are widely used in the meat industry due to their low cost, stability, and uniformity (Jo, Lee, Yong, et al., 2020). However, health concerns particularly regarding the formation of carcinogenic nitrosamines have led consumers to prefer natural and organic products (Sebranek & Bacus, 2007). Studies show that many consumers are willing to pay more for organic foods and generally favor replacing synthetic nitrites with plant-based alternatives (Hung et al., 2016). Nitrosamines are formed through the reaction of nitrite with secondary amines at high temperatures and low pH (Honikel, 2008). Although no compound can fully replace nitrite, strategies such as reducing added or residual nitrite levels and using natural sources are increasingly being adopted in the meat industry (Jo, Lee, Yong, et al., 2020).

Certain vegetables, such as celery, beetroot, and lettuce, are rich in nitrate, which can be reduced to nitrite by nitrate-reducing bacteria and used as a natural nitrite source in processed meats (Sebranek & Bacus, 2007). To ensure sufficient nitrate-to-nitrite conversion, vegetable juice or powder is added with starter cultures and incubated at 38–42 °C prior to cooking (Sebranek et al., 2012). Incubation time is particularly important for smaller products like sausages, while larger products such as hams achieve adequate nitrite levels during cooking (Sindelar et al., 2007). Pre-processed celery powder is widely used as a synthetic nitrite alternative, providing similar quality and antimicrobial effects (Sebranek et al., 2012). Other vegetables, including fermented beetroot and spinach, can also supply sufficient nitrite, improving color, inhibiting lipid oxidation, and controlling microbial growth (Choi et al., 2017). Naturally cured products generally contain lower residual nitrite, reducing the risk of nitrosamine formation (Li et al., 2013). However, nitrate content and reduction efficiency can vary with environmental and processing factors, and excessive addition of vegetables may affect flavor and color (Alahakoon et al., 2015). Microbial safety in naturally cured meats may require additional treatments, therefore, using natural nitrite sources requires process optimization to ensure product quality, safety, and consistency (Jo, Lee, Yong, et al., 2020). According to the reviewed sources, plants such as *Salvia rosmarinus Spenn., Camellia sinensis (L.) Kuntze, Crocus sativus L., Curcuma longa L.,* and *Thymus spp.* are the most widely used in meat products, and their extraction method plays an important role in the effectiveness and preservation of their bioactive compounds (Tocai et al., 2025). The color of meat products is one of the quality factors that determines the acceptance of the product by the consumer. Plants can affect this product characteristic through the direct coloring effects of plant pigments or due to indirect mechanisms, such as myoglobin stabilization and inhibition of lipid oxidation, which prevent color changes during storage. Several studies have investigated natural antioxidants from plants such as *D. ambrosioides (L.) Mosyakin & Clemants, Curcuma longa L., P. nigrum L., N. velutina Wooton, Q. alba L., S. rosmarinus Spenn., S. aromaticum L., T. vulgaris L.* and *T. foenum de liing* or their extracts affect instrumental color parameters, especially L* (lightness), a* (redness) and b* (yellowness) in different meat matrices (Tocai et al., 2025).

Some researchers have used vegetables such as celery, parsley, beetroot, and spinach, containing nitrate levels of approximately 1500–2800 ppm, as natural nitrite sources in processed meats, results showed that, after incubation for 30–120 min at 38–42 °C, these sources could maintain color quality, antimicrobial properties, and inhibition of lipid oxidation throughout a storage period of up to 28 days, achieving performance comparable to synthetic nitrite (Riel et al., 2017). The recommended addition level of celery powder is 0.2–0.4%, as higher amounts may negatively affect flavor (Alahakoon et al., 2015). However, the type of vegetable and processing conditions can influence both efficacy and microbial safety of the product (**Table 1**). In a study also, bacterial nanocellulose films containing sodium nitrite, sumac extract, and black carrot extract were developed as active packaging for cooked beef ham, the films effectively reduced microbial load, oxidation, and residual nitrite while maintaining desirable product color, demonstrating great potential for reducing nitrite usage in the meat industry (Shiravani et al., 2024).

Emerging technologies for nitrite reduction

In recent years, growing health concerns over the formation of carcinogenic nitrosamines have prompted the food industry to seek alternative approaches for reducing or replacing synthetic nitrite in meat products (**Figure 2**). Emerging non-thermal technologies such as HPP, pulsed electric fields (PEF), cold plasma, and low-dose irradiation, as well as innovative packaging strategies, have attracted considerable attention as promising tools to maintain microbial safety and product quality while lowering nitrite levels. These techniques offer clean-label solutions that can inhibit N-nitrosamine formation and extend shelf life, although potential impacts on sensory attributes and stability should also be considered (Andrade et al., 2025).

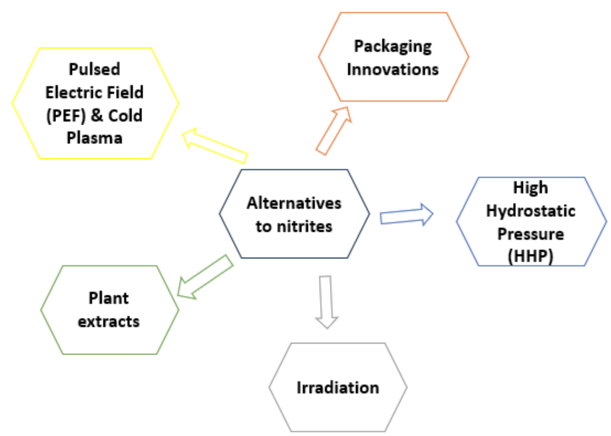

Figure 2. Alternatives to reduce the nitrite level in processed meat

High hydrostatic pressure

HHP is an isostatic process in which packaged foods are subjected to pressures of 100–900 MPa, affecting the metabolism and cell membranes of microorganisms (Rendueles et al., 2011). This process leads to cell death through multiple internal damages, including changes in ion exchange, fatty acid composition, protein denaturation, and enzyme inhibition (Simpson & Gilmour, 1997). HHP can inactivate pathogenic and spoilage microorganisms without significantly compromising the sensory quality of foods (Cheftel & Culioli, 1997). Combining HHP with salt or other hurdles creates a synergistic effect that limits bacterial regrowth, HHP allows for the reduction of added salt and nitrite in meat products without compromising microbiological safety (Pietrzak et al., 2007). Treatment with HHP at 500–600 MPa for a few minutes significantly reduces the growth of meat flora, spoilage bacteria, and *L. monocytogenes*, HHP can preserve the shelf life of low-salt or reduced-nitrite hams for several weeks under refrigerated conditions. Studies have shown that combining HHP with enterocin LM-2 reduces *L. monocytogenes* and Salmonella to undetectable levels and extends the shelf life of sliced cooked ham up to 70–90 days (Liu et al., 2012). HHP represents a non-thermal alternative for ensuring the microbial safety of ready-to-eat meat products while maintaining sensory quality, ongoing research continues to evaluate the effects of HHP on the inactivation of resistant spores, such as *C. botulinum*, and other resilient microorganisms (Alahakoon et al., 2015). A review article evaluated cold plasma (CP) and HPP for their effectiveness in meat preservation through a systematic analysis of 96 studies (2015-2025) from Scopus and Web of Science. The results showed that cold plasma CP with minimal lipid oxidation resulted in a 2-3 log reduction in surface pathogens (e. g. *L. monocytogenes*, *E. coli*), while HPP ensured massive microbial inactivation (up to 5 log reduction) (Ghazali et al., 2025).

Table 1. Effect of different plant-based alternatives of nitrites on meat products.

Additives	Meat Products	Effects	Reference
Parsley extract powder	Mortadella type sausages	*L. monocytogenes* reduction, reduced residual nitrite level	(Riel et al., 2017)
Beetroot powder	Fermented beef sausage	Control lipid oxidation and nitrite contents	(Sucu & Turp, 2018)
Celery juice concentrate orpowder	Ham slices	Control lipid oxidation, color development	(Horsch et al., 2014)
Rosemary essential oil + lyophilized extract	Pork sausages	Lipid oxidation inhibition higher antioxidant activity	(Bianchin et al., 2017)
Celery juice powder + starter cultures	Ready-to-eat ham	Control lipid oxidation, color development	(Sindelar et al., 2007)
Red wine + garlic	Chouriços cold-dried, smoked sausages	Color development, strong cured flavor, inhibitory properties against *Salmonella*	(Patarata et al., 2020)
Freeze-dried cranberry	Fallow-deer fermented sausage	Control lipid oxidation	(Karwowska & Dolatowski, 2016)
Tomato pulp powder	Pork luncheon roll, frankfurters	Control lipid oxidation	(Hayes et al., 2013)
Fermented spinach powder	Cured pork loins	Control lipid oxidation	(Kim et al., 2016)
Pomegranate pee extract	Beef sausage	TBARS reduction, hydroperoxides reduction.	(Aliyari et al., 2025)

Pulsed electric field and cold plasma

PEF is an emerging non-thermal technology that uses short, high-voltage pulses (5–50 kV/cm) to treat food products while minimizing thermal damage (**Figure 3**). It improves meat tenderness, enhances salt diffusion, increases water-holding capacity, and effectively inactivates microorganisms without compromising sensory or nutritional quality. Owing to its low energy consumption and short processing time, PEF is considered a sustainable and efficient method for meat, poultry, and seafood processing (Ahmed et al., 2025). Moreover, by enhancing microbial safety and curing efficiency, PEF can contribute to reducing the required nitrite dosage in meat products, thus supporting cleaner-label and healthier formulations.

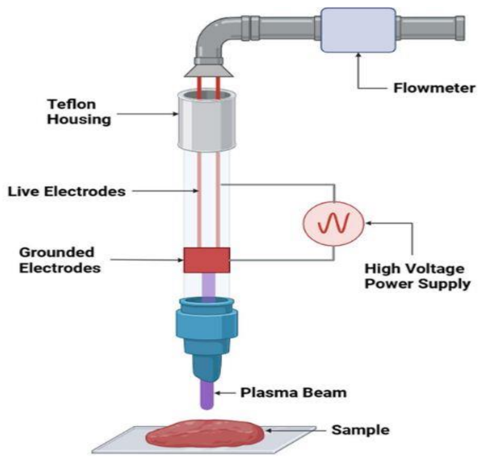

Figure 3. Schematic diagram of cold plasma device form (Ghazali et al., 2025; Reema et al., 2022)

Plasma is an ionized gas generated by applying an electrical discharge to a neutral gas, and atmospheric non-thermal plasma (ANP) has emerged as a novel technology with potential applications in the food industry (Lee et al., 2017). ANP has been widely studied as a non-thermal pasteurization technique and recently proposed as a novel curing method for meat products (Misra et al., 2019). Plasma contains reactive nitrogen species that act as nitrite precursors, which are generated through a series of reactions involving nitric oxide, ozone, and water, ultimately producing nitrite in liquids or meat matrices (Jo, Lee, Lee, et al., 2020). Studies have shown that ANP-treated water or direct plasma treatment of meat or meat batters can produce nitrite levels comparable to conventional sodium nitrite curing, resulting in similar color, lipid oxidation, and sensory properties (Yong et al., 2019). Indirect plasma treatment has been developed to minimize temperature increases during treatment, enabling stable nitrite generation even at high plasma power without exceeding recommended meat temperatures (Jo, Lee, Lee, et al., 2020). Plasma-treated natural plant extracts, such as Perilla frutescens, garlic, and onion, can serve as nitrite sources, expanding the range of potential natural curing agents (Jung et al., 2017). The efficiency of nitrite production depends on plasma parameters, treatment time, pH, and buffering capacity of the medium or plant material (Jung et al., 2015). Nitrite levels produced by ANP can be precisely controlled through treatment duration and system-specific regression models, providing reproducible results (Jo, Lee, Lee, et al., 2020). While ANP effectively generates nitrite and improves microbial safety in meat products, the potential chemical interactions of reactive plasma species with lipids and proteins must be carefully evaluated (**Figure 4**). Preliminary safety assessments indicate no genotoxicity or adverse immune responses in plasma-treated meat or plant-based extracts, although comprehensive studies are still needed (Yong et al., 2019). Overall, ANP represents a promising non-thermal curing and microbial inactivation technology, capable of producing nitrite from liquids, meat, or plant matrices while maintaining product quality and safety (Jo, Lee, Lee, et al., 2020).

Packaging innovations

In recent years, meat and meat product packaging has moved toward sustainable and eco-friendly solutions through the use of natural biopolymers and bioactive compounds. These packaging materials enhance the safety and shelf life of products compared to conventional systems by reducing oxidation, microbial growth, and moisture loss (Gil & Rudy, 2023). Innovation in this field is categorized into three main types: active packaging, which employs absorbers or emitters to control the internal environment; intelligent packaging, which utilizes sensors to assess product quality, freshness, and safety; and interactive packaging, which integrates technologies such as rapid communication coding or smart cooking guides to enhance consumer awareness and convenience. Although many of these technologies have been patented, further validation is required for their direct application in meat packaging. Ultimately, combining these three approaches into multifunctional systems can improve efficiency, cost-effectiveness, and consumer acceptance.

Several studies have focused on developing active packaging films containing nitrite to preserve the quality, color, and safety of meat products. In one study, bacterial nanocellulose (BNC) films impregnated with sodium nitrite (SN), sumac extract (SE), and black carrot extract (BCE) improved the mechanical properties of the films, reduced microbial growth by more than 3.5 log cycles compared to the control, and decreased oxidation by up to 60% (Shiravani & Kazemi, 2025). Another study reported that BNC films containing $SE_{10}BCE_{5}SN_{125}$ (sumac extract (SE 10% w/v), black carrot extract (BCE 5% w/v) and sodium nitrite (SN 125 ppm)) applied to cooked beef ham significantly reduced microbial counts (by over 4 log cycles), lowered oxidation by 70%, and decreased residual nitrite by 64% compared to the positive control, while maintaining high redness (Shiravani et al., 2024). Additionally, starch-based active films embedded with sodium nitrite produced homogeneous matrices with enhanced mechanical properties and, through the release of small amounts of nitrite (<1.1 ppm), increased meat redness by more than 30%, inhibited metmyoglobin formation, and prevented microbial growth and lipid oxidation during chilled storage. Overall, these findings indicate that nitrite-incorporated active films effectively preserve the color and quality of meat while reducing nitrite requirements, offering an innovative approach to meat packaging (Chatkitanan & Harnkarnsujarit, 2020).

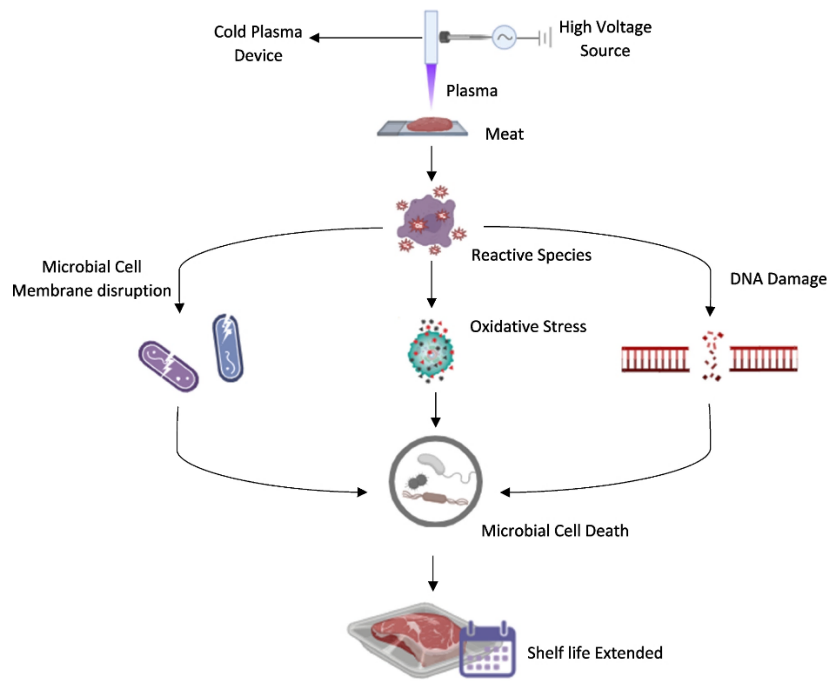

Figure 4. Mechanism of microbial inactivation by cold plasma technique form (Ghazali et al., 2025).

Other novel approaches and detecting nitrite

Food irradiation, including gamma rays, X-rays, and electron beams, is a validated technology for improving food safety, with gamma irradiation showing the highest potential. Despite public concerns limiting its commercialization, international approvals have increased consumer trust and industry interest (Zhang et al., 2023). Gamma irradiation is effective in reducing residual nitrite and N-nitrosamines in processed meats. Studies have shown that high-dose gamma irradiation (≥10 kGy) significantly decreases nitrite levels in model sausages, while moderate doses (5 kGy) reduce residual nitrite in products like Chinese Rogao ham (Wei et al., 2009), however, recent research on irradiation's impact on nitrite reduction remains limited.

In a study, nitrite ion detection was investigated as a key indicator for monitoring food safety and health. Three dyes, bromophenol blue (BPB), Eriochrome black T (EBT), and Potassium permanganate ($KMnO_4$), were used to identify nitrite under various laboratory conditions. UV–visible spectroscopy results showed that EBT exhibited the lowest detection limit (0.2054 mM). Moreover, an Internet of Things (IoT)-based colorimetric system was developed to enable real-time RGB (red, green, and blue) measurement. This system provides an accurate, cost-effective, and portable approach for monitoring nitrite levels in food samples (Paramparambath et al., 2024).

In a study, a radiometric fluorescent probe based on phenylene-diamine-derived carbon dots (Ph-CDs) and rhodamine B (RhB) was developed for the rapid and accurate detection of nitrite in food and water, under acidic conditions, NO_2 induces rapid fluorescence quenching of Ph-CDs through a diazotization reaction within 200 seconds, while RhB serves as a stable internal reference, ensuring matrix-independent accuracy, by integrating smartphone imaging, this system enables real-time visual detection and quantification without the need for complex instrumentation, a low detection limit (0.10 µM) and high recovery rates (96.8–101.8%) in real food and water samples confirmed the high sensitivity and reliability of the method, this portable and user-friendly platform provides an innovative and effective approach for on-site NO_2 monitoring, enhancing food safety and environmental surveillance (Wu et al., 2025).

Conclusion

The Nitrite is a multifunctional additive widely used in meat processing, responsible for the characteristic pink-red color, flavor, antioxidant activity, and bacteriostatic effects against pathogens such as *Clostridium botulinum*. Despite its benefits, concerns regarding its potential carcinogenicity and health risks, including methemoglobinemia in children and colorectal cancer in adults, have led to increased consumer demand for natural or low-nitrite meat products. Consequently, the meat industry faces the challenge of reducing residual nitrite while maintaining safety, quality, and sensory properties. Emerging strategies, including plant extracts, HHP, and active nitrogen plasma, have shown potential as partial or complete nitrite alternatives. However, no single substitute can replicate all the multifunctional roles of nitrite, and natural sources often face limitations related to nitrate content, sensory impact, and process stability. Hybrid approaches that combine reduced levels of sodium nitrite with other additives or processing technologies may provide effective antimicrobial activity while preserving desirable sensory characteristics. Nevertheless, further research is required to evaluate the safety, efficacy, and cost-effectiveness of these strategies, as well as to systematically assess the correlation between nitrite consumption and human health outcomes, particularly regarding colorectal cancer and other diet-related risks.

Conflicts of interest

I declare that I have no conflicts of interest.

Disclaimer

I declare that no generative AI was used to create or analyze the scientific content of this manuscript. ChatGPT (OpenAI) was used only to improve the English language and grammar of the text.

References

Ahmed, M., Ranjan, H., & Roy, S. (2025). Pulsed electric fields for sustainable meat, poultry, and fish processing: Recent advances, prospects, and industry challenges. *Innovative Food Science & Emerging Technologies*, 104008. https://doi.org/10.1016/j.ifset.2025.104008

Alahakoon, A. U., Jayasena, D. D., Ramachandra, S., & Jo, C. (2015). Alternatives to nitrite in processed meat: Up to date. *Trends in Food Science & Technology*, *45*(1), 37–49. https://doi.org/10.1016/j.tifs.2015.05.008

Aliyari, P., Bakhshi Kazaj, F., Barzegar, M., & Ahmadi Gavlighi, H. (2025). Production of functional sausage using pomegranate peel and pistachio green hull extracts as natural preservatives. *Journal of Agricultural Science and Technology*, *22*(1), 159–172

Alvarado, C., & McKee, S. (2007). Marination to improve functional properties and safety of poultry meat. *Journal of Applied Poultry Research*, *16*(1), 113–120. https://doi.org/10.1093/japr/16.1.113

Andrade, B. F., do Carmo, L. R., Tanaka, M. S., Ramos, A. de L. S., & Ramos, E. M. (2025). Evaluation of Nonthermal Technologies to Reduce or Replace Nitrite in Meat Products. *Food Technology and Biotechnology*, *63*(1), 94–108. https://doi.org/10.17113/ftb.63.01.25.8744

Bianchin, M., Pereira, D., dos Reis, A. S., de Florio Almeida, J., da Silva, L. D., de Moura, C., & Carpes, S. T. (2017). Rosemary essential oil and lyophilized extract as natural antioxidant source to prevent lipid oxidation in pork sausage. *Advance Journal of Food Science and Technology*, *13*(5), 210–217. https://doi.org/10.19026/ajfst.13.5070

Bintsis, T. (2017). Foodborne pathogens. *AIMS Microbiology*, *3*(3), 529. https://doi.org/10.3934/microbiol.2017.3.529

Brown, G. C., & Borutaite, V. (2006). Interactions between nitric oxide, oxygen, reactive oxygen species and reactive nitrogen species. *Biochemical Society Transactions*, *34*(Pt 5), 953–956. https://doi.org/10.1042/bst0340953

Carrascosa, C., Raheem, D., Ramos, F., Saraiva, A., & Raposo, A. (2021). Microbial biofilms in the food industry—A comprehensive review. *International Journal of Environmental Research and Public Health*, *18*(04), 2014. https://doi.org/10.3390/ijerph18042014

Casoni, D., Badiu, R. R., & Frentiu, T. (2019). Spectrophotometric determination and assessment of potential health risk of nitrite from meat and processed meat products. *Studia Universitatis Babes-Bolyai Chemia, 2*, 265–277. https://doi.org/10.24193/subbchem.2019.2.22

Chatkitanan, T., & Harnkarnsujarit, N. (2020). Development of nitrite compounded starch-based films to improve color and quality of vacuum-packaged pork. *Food Packaging and Shelf Life*, *25*, 100521. https://doi.org/10.1016/j.fpsl.2020.100521

Cheftel, J. C., & Culioli, J. (1997). Effects of high pressure on meat: A review. *Meat Science*, *46*(3), 211–236. https://doi.org/10.1016/S0309-1740(97)00017-X

Choi, Y.-S., Kim, T.-K., Jeon, K.-H., Park, J.-D., Kim, H.-W., Hwang, K.-E., & Kim, Y.-B. (2017). Effects of pre-converted nitrite from red beet and ascorbic acid on quality characteristics in meat emulsions. *Korean Journal for Food Science of Animal Resources*, *37*(2), 288. https://doi.org/10.5851/kosfa.2017.37.2.288

Corrêa Cardoso, A. C., Monteiro, M. L. G., Torres Neto, L., & Conte-Junior, C. A. (2025). Can essential oils be an alternative for reducing nitrites in different types of cured meats? *Food Reviews International*, 1–40. https://doi.org/10.1080/87559129.2025.2518478

Dawan, J., Zhang, S., & Ahn, J. (2025). Recent advances in biofilm control technologies for the food industry. *Antibiotics*, *14*(3), 254. https://doi.org/10.3390/antibiotics14030254

Del Valle, M., Cámara, M., & Torija, M. A. E. (2002). Effect of pomace addition on tomato paste quality. *VIII International Symposium on the Processing Tomato 613*, 399–406. https://doi.org/10.17660/ActaHortic.2003.613.63

Dimitrakopoulou, M.-E., & Vantarakis, A. (2022). Microbiological Factors of Food Quality for Risk Assessments in Europe: A Systematic Review. *Food Science and Quality Management*, *113*, 103–113. https://doi.org/10.7176/FSQM/113-03

dos Santos Baião, D., Vieira Teixeira da Silva, D., & Margaret Flosi Paschoalin, V. (2021). A narrative review on dietary strategies to provide nitric oxide as a non-drug cardiovascular disease therapy: Beetroot formulations—A smart nutritional intervention. *Foods*, *10*(4), 859. https://doi.org/10.3390/foods10040859

Ferrer-Sueta, G., & Radi, R. (2009). Chemical biology of peroxynitrite: kinetics, diffusion, and radicals. *ACS Chemical Biology*, *4*(3), 161–177. https://doi.org/10.1021/cb800279q

Gassara, F., Kouassi, A. P., Brar, S. K., & Belkacemi, K. (2016). Green alternatives to nitrates and nitrites in meat-based products–a review. *Critical Reviews in Food Science and Nutrition*, *56*(13), 2133–2148. https://doi.org/10.1080/10408398.2013.812610

Ghazali, M. H., Saleem, F., & Bashir, L. (2025). Cold plasma and high-pressure processing in sustainable meat preservation: a review. *Food, Nutrition and Health*, *2*(1), 22. https://doi.org/10.1007/s44403-025-00032-1

Gil, M., & Rudy, M. (2023). Innovations in the packaging of meat and meat products—A review. *Coatings*, *13*(2), 333. https://doi.org/10.3390/coatings13020333

Govari, M., & Pexara, A. (2015). Nitrates and Nitrites in meat products. *Journal of the Hellenic Veterinary Medical Society*, *66*(3), 127–140. https://doi.org/10.12681/jhvms.15856

Hamad, A., & Singh, P. (2025). Boosting nutritional value: the role of iron fortification in meat and meat products. *BioMetals*, *38*(2), 337–355. https://doi.org/10.1007/s10534-024-00659-1

Hayes, J. E., Canonico, I., & Allen, P. (2013). Effects of organic tomato pulp powder and nitrite level on the physicochemical, textural and sensory properties of pork luncheon roll. *Meat Science*, *95*(3), 755–762. https://doi.org/10.1016/j.meatsci.2013.04.049

Herold, S., & Shivashankar, K. (2003). Metmyoglobin and methemoglobin catalyze the isomerization of peroxynitrite to nitrate. *Biochemistry*, *42*(47), 14036–14046. https://doi.org/10.1021/bi0350349

Honikel, K.-O. (2008). The use and control of nitrate and nitrite for the processing of meat products. *Meat Science*, *78*(1–2), 68–76. https://doi.org/10.1016/j.meatsci.2007.05.030

Horsch, A. M., Sebranek, J. G., Dickson, J. S., Niebuhr, S. E., Larson, E. M., Lavieri, N. A., Ruther, B. L., & Wilson, L. A. (2014). The effect of pH and nitrite concentration on the antimicrobial impact of celery juice concentrate compared with conventional sodium nitrite on Listeria monocytogenes. *Meat Science*, *96*(1), 400–407. https://doi.org/10.1016/j.meatsci.2013.07.036

Hospital, X. F., Hierro, E., & Fernandez, M. (2014). Effect of reducing nitrate and nitrite added to dry fermented sausages on the survival of Salmonella Typhimurium. *Food Research International*, *62*, 410–415. https://doi.org/10.1016/j.foodres.2014.03.055

Hung, Y., de Kok, T. M., & Verbeke, W. (2016). Consumer attitude and purchase intention towards processed meat products with natural compounds and a reduced level of nitrite. *Meat Science*, *121*, 119–126. https://doi.org/10.1016/j.meatsci.2016.06.002

Jayasena, D. D., & Jo, C. (2013). Essential oils as potential antimicrobial agents in meat and meat products: A review. *Trends in Food Science & Technology*, *34*(2), 96–108. https://doi.org/10.1016/j.tifs.2013.09.002

Jo, K., Lee, J., Lee, S., Lim, Y., Choi, Y.-S., Jo, C., & Jung, S. (2020). Curing of ground ham by remote infusion of atmospheric non-thermal plasma. *Food Chemistry*, *309*, 125643. https://doi.org/10.1016/j.foodchem.2019.125643

Jo, K., Lee, S., Yong, H. I., Choi, Y.-S., & Jung, S. (2020). Nitrite sources for cured meat products. *LWT-Food Science and Technology*, *129*, 109583. https://doi.org/10.1016/j.lwt.2020.109583

Jung, S., Kim, H. J., Park, S., Yong, H. I., Choe, J. H., Jeon, H.-J., Choe, W., & Jo, C. (2015). Color developing capacity of plasma-treated water as a source of nitrite for meat curing. *Korean Journal for Food Science of Animal Resources*, *35*(5), 703. https://doi.org/10.5851/kosfa.2015.35.5.703

Jung, S., Lee, J., Lim, Y., Choe, W., Yong, H. I., & Jo, C. (2017). Direct infusion of nitrite into meat batter by atmospheric pressure plasma treatment. *Innovative Food Science & Emerging Technologies*, *39*, 113–118. https://doi.org/10.1016/j.ifset.2016.11.010

Karwowska, M., & Dolatowski, Z. J. (2016). Effect of acid whey and freeze-dried cranberries on lipid oxidation and fatty acid composition of nitrite-/nitrate-free fermented sausage made from deer meat. *Asian-Australasian Journal of Animal Sciences*, *30*(1), 85. https://doi.org/10.5713/ajas.16.0023.

Kim, H.-J., Sung, N.-Y., Yong, H. I., Kim, H., Lim, Y., Ko, K. H., Yun, C.-H., & Jo, C. (2016). Mutagenicity and immune toxicity of emulsion-type sausage cured with plasma-treated water. *Korean Journal for Food Science of Animal Resources*, *36*(4), 494. https://doi.org/10.5851/kosfa.2016.36.4.494

Lee, J., Lee, C. W., Yong, H. I., Lee, H. J., Jo, C., & Jung, S. (2017). Use of atmospheric pressure cold plasma for meat industry. *Korean Journal for Food Science of Animal Resources*, *37*(4), 477. https://doi.org/10.5851/kosfa.2017.37.4.477

Li, L., Shao, J., Zhu, X., Zhou, G., & Xu, X. (2013). Effect of plant polyphenols and ascorbic acid on lipid oxidation, residual nitrite and N-nitrosamines formation in dry-cured sausage. *International Journal of Food Science and Technology*, *48*(6), 1157–1164. https://doi.org/10.1111/ijfs.12069

Liu, G., Wang, Y., Gui, M., Zheng, H., Dai, R., & Li, P. (2012). Combined effect of high hydrostatic pressure and enterocin LM-2 on the refrigerated shelf life of ready-to-eat sliced vacuum-packed cooked ham. *Food Control*, *24*(1–2), 64–71. https://doi.org/10.1016/j.foodcont.2011.09.004.

Lüth, S., Halbedel, S., Rosner, B., Wilking, H., Holzer, A., Roedel, A., Dieckmann, R., Vincze, S., Prager, R., & Flieger, A. (2020). Backtracking and forward checking of human listeriosis clusters identified a multiclonal outbreak linked to Listeria monocytogenes in meat products of a single producer. *Emerging Microbes & Infections*, *9*(1), 1600–1608. https://doi.org/10.1080/22221751.2020.1784044

Majou, D., & Christieans, S. (2018). Mechanisms of the bactericidal effects of nitrate and nitrite in cured meats. *Meat Science*, *145*, 273–284. https://doi.org/10.1016/j.meatsci.2018.06.013

Martinović, T., Andjelković, U., Gajdošik, M. Š., Rešetar, D., & Josić, D. (2016). Foodborne pathogens and their toxins. *Journal of Proteomics*, *147*, 226–235. https://doi.org/10.1016/j.jprot.2016.04.029

Misra, N. N., Yadav, B., Roopesh, M. S., & Jo, C. (2019). Cold plasma for effective fungal and mycotoxin control in foods: mechanisms, inactivation effects, and applications. *Comprehensive Reviews in Food Science and Food Safety*, *18*(1), 106–120. https://doi.org/10.1111/1541-4337.12398

Mortensen, A., Aguilar, F., Crebelli, R., Di Domenico, A., Dusemund, B., Frutos, M. J., Galtier, P., Gott, D., et al. (2017). Re-evaluation of potassium nitrite (E 249) and sodium nitrite (E 250) as food additives. *Efsa Journal*, *15*(6), e04786. https://doi: 10.2903/j.efsa.2017.4786

Munekata, P. E. S., Rocchetti, G., Pateiro, M., Lucini, L., Domínguez, R., & Lorenzo, J. M. (2020). Addition of plant extracts to meat and meat products to extend shelf-life and health-promoting attributes: An overview. *Current Opinion in Food Science*, *31*, 81–87. https://doi.org/10.1016/j.cofs.2020.03.003

Oliulla, H., Mizan, M. F. R., Kang, I., & Ha, S.-D. (2024). On-going issues regarding biofilm formation in meat and meat products: challenges and future perspectives. *Poultry Science*, *103*(12), 104373. https://doi.org/10.1016/j.psj.2024.104373

Oliveira, S. M., Lopes, T., & Rangel, A. O. S. S. (2004). Spectrophotometric determination of nitrite and nitrate in cured meat by sequential injection analysis. *Journal of Food Science*, *69*(9), C690–C695. https://doi.org/10.1111/j.1365-2621.2004.tb09917.x

Paramparambath, S., Geetha, M., Alahzm, A. M., Al-Ejji, M., & Sadasivuni, K. K. (2024). Innovative smart colorimetric sensor for nitrite detection in poultry packaging. *Discover Applied Sciences*, *6*(5), 263. https://doi.org/10.1007/s42452-024-05943-w

Patarata, L., Martins, S., Silva, J. A., & Fraqueza, M. J. (2020). Red wine and garlic as a possible alternative to minimize the use of nitrite for controlling Clostridium sporogenes and Salmonella in a cured sausage: Safety and sensory implications. *Foods*, *9*(2), 206. https://doi.org/10.3390/foods9020206

Pereira, N. R., Tarley, C. R. T., Matsushita, M., & de Souza, N. E. (2000). Proximate composition and fatty acid profile in Brazilian poultry sausages. *Journal of Food Composition and Analysis*, *13*(6), 915–920. https://doi.org/10.1006/jfca.2000.0919

Pietrzak, D., Fonberg-Broczek, M., Mucka, A., & Windyga, B. (2007). Effects of high pressure treatment on the quality of cooked pork ham prepared with different levels of curing ingredients. *High Pressure Research*, *27*(1), 27–31. https://doi.org/10.1080/08957950601091087

Prolo, C., Álvarez, M. N., & Radi, R. (2014). Peroxynitrite, a potent macrophage-derived oxidizing cytotoxin to combat invading pathogens. *Biofactors*, *40*(2), 215–225. https://doi.org/10.1002/biof.1150

Radi, R. (2013). Peroxynitrite, a stealthy biological oxidant. *Journal of Biological Chemistry*, *288*(37), 26464–26472. https://doi.org/ 10.1074/jbc.R113.472936

Reema, Khanikar, R. R., Bailung, H., & Sankaranarayanan, K. (2022). Review of the cold atmospheric plasma technology application in food, disinfection, and textiles: A way forward for achieving circular economy. *Frontiers in Physics*, *10*, 942952. https://doi.org/10.3389/fphy.2022.942952

Rendueles, E., Omer, M. K., Alvseike, O., Alonso-Calleja, C., Capita, R., & Prieto, M. (2011). Microbiological food safety assessment of high hydrostatic pressure processing: A review. *LWT-Food Science and Technology*, *44*(5), 1251–1260. https://doi.org/10.1016/j.lwt.2010.11.001

Riel, G., Boulaaba, A., Popp, J., & Klein, G. (2017). Effects of parsley extract powder as an alternative for the direct addition of sodium nitrite in the production of mortadella-type sausages–Impact on microbiological, physicochemical and sensory aspects. *Meat Science*, *131*, 166–175. https://doi.org/10.1016/j.meatsci.2017.05.007

Sampaio, G. R., Castellucci, C. M. N., e Silva, M. E. M. P., & Torres, E. A. F. S. (2004). Effect of fat replacers on the nutritive value and acceptability of beef frankfurters. *Journal of Food Composition and Analysis*, *17*(3–4), 469–474. https://doi.org/10.1016/j.jfca.2004.03.016

Sebranek, J. G., & Bacus, J. N. (2007). Cured meat products without direct addition of nitrate or nitrite: what are the issues? *Meat Science*, *77*(1), 136–147. https://doi.org/10.1016/j.meatsci.2007.03.025

Sebranek, J. G., Jackson-Davis, A. L., Myers, K. L., & Lavieri, N. A. (2012). Beyond celery and starter culture: Advances in natural/organic curing processes in the United States. *Meat Science*, *92*(3), 267–273. https://doi.org/10.1016/j.meatsci.2012.03.002

Shakil, M. H., Trisha, A. T., Rahman, M., Talukdar, S., Kobun, R., Huda, N., & Zzaman, W. (2022). Nitrites in cured meats, health risk issues, alternatives to nitrites: A review. *Foods*, *11*(21), 3355. https://doi.org/10.3390/foods11213355

Shiravani, Z., Aliakbarlu, J., & Moradi, M. (2024). Application of bacterial nanocellulose film loaded with sodium nitrite, sumac, and black carrot extracts to reduce sodium nitrite, extend shelf life, and inhibit Clostridium perfringens in cooked beef ham. *International Journal of Biological Macromolecules*, *280*, 135841. https://doi.org/10.1016/j.ijbiomac.2024.135841

Shiravani, Z., & Kazemi, M. (2025). Effect of bacterial nanocellulose film containing sodium nitrite, and water extracts of sumac and black carrot on the shelf life of ground beef. *Food Safety and Packaging*, *1*(2), 115–126. https://doi.org/10.30466/fsp.2025.56371.1012

Simpson, R. K., & Gilmour, A. (1997). The effect of high hydrostatic pressure on Listeria monocytogenes in phosphate-buffered saline and model food systems. *Journal of Applied Microbiology*, *83*(2), 181–188. https://doi.org/10.1046/j.1365-2672.1997.00215.x

Sindelar, J. J., Cordray, J. C., Sebranek, J. G., Love, J. A., & Ahn, D. U. (2007). Effects of varying levels of vegetable juice powder and incubation time on color, residual nitrate and nitrite, pigment, pH, and trained sensory attributes of ready-to-eat uncured ham. *Journal of Food Science*, *72*(6), S388–S395. https://doi.org/10.1111/j.1750-3841.2007.00404.x

Sofos, J. N., Busta, F. F., & Allen, C. E. (1979). Botulism control by nitrite and sorbate in cured meats: a review. *Journal of Food Protection*, *42*(9), 739–770. https://doi.org/10.4315/0362-028X-42.9.739

Stamenić, T., Petričević, M., Keškić, T., Pisinov, B., Stanojković, A., Kos, I., & Radojičić, M. (2024). Assessment of residual nitrite levels in cooked sausages: Compliance, thermal processing effects, and consumer safety. *Biotechnology in Animal Husbandry*, *40*(1), 65–76. https://doi.org/10.2298/BAH2401065S

Su, J., & Groves, J. T. (2010). Mechanisms of peroxynitrite interactions with heme proteins. *Inorganic Chemistry*, *49*(14), 6317–6329. https://doi.org/10.1021/ic902157z

Sucu, C., & Turp, G. Y. (2018). The investigation of the use of beetroot powder in Turkish fermented beef sausage (sucuk) as nitrite alternative. *Meat Science*, *140*, 158–166. https://doi.org/10.1016/j.meatsci.2018.03.012

Suman, S. P., Nair, M. N., Joseph, P., & Hunt, M. C. (2016). Factors influencing internal color of cooked meats. *Meat Science*, *120*, 133–144. https://doi.org/10.1016/j.meatsci.2016.04.006

Tocai, A. C., Rosan, C. A., Teodorescu, A. G., Venter, A. C., & Vicas, S. I. (2025). Multifunctional Roles of Medicinal Plants in the Meat Industry: Antioxidant, Antimicrobial, and Color Preservation Perspectives. *Plants*, *14*(17), 2737. https://doi.org/10.3390/plants14172737

Wei, F., Xu, X., Zhou, G., Zhao, G., Li, C., Zhang, Y., Chen, L., & Qi, J. (2009). Irradiated Chinese Rugao ham: Changes in volatile N-nitrosamine, biogenic amine and residual nitrite during ripening and post-ripening. *Meat Science*, *81*(3), 451–455. https://doi.org/10.1016/j.meatsci.2008.09.005

Wu, H., Hao, Y., Cheng, X., Wang, H., Dong, W., Shuang, S., Hu, Q., Dong, C., & Gong, X. (2025). Phenylenediamine-derived carbon dots coupled with rhodamine B: Ultrafast ratiometric fluorescence and smartphone-enabled imaging detection of nitrite. *Food Chemistry*, 145774. https://doi.org/10.1016/j.foodchem.2025.145774

Yong, H. I., Lee, S. H., Kim, S. Y., Park, S., Park, J., Choe, W., & Jo, C. (2019). Color development, physiochemical properties, and microbiological safety of pork jerky processed with atmospheric pressure plasma. *Innovative Food Science & Emerging Technologies*, *53*, 78–84. https://doi.org/10.1016/j.ifset.2017.09.005

Zhang, Y., Zhang, Y., Jia, J., Peng, H., Qian, Q., Pan, Z., & Liu, D. (2023). Nitrite and nitrate in meat processing: Functions and alternatives. *Current Research in Food Science*, *6*, 100470. https://doi.org/10.1016/j.crfs.2023.100470