Received: 13 April 2022 | Revised: 29 July 2022 | Accepted: 19 August 2022
DOI: 10.1111/1750-3841.16329

CONCISE REVIEWS & HYPOTHESES IN FOOD SCIENCE

Journal of Food Science WILEY

Multitarget preservation technologies for chemical-free sustainable meat processing

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Abstract

Due to the growing consumer demand for safe and naturally processed meats, the meat industry is seeking novel methods to produce safe-to-consume meat products without affecting their sensory appeal. The green technologies can maintain the sensory and nutritive characteristics and ensure the microbial safety of processed meats and, therefore, can help to reduce the use of chemical preservatives in meat products. The use of chemical additives, especially nitrites in processed meat products, has become controversial because they may form carcinogenic N-nitrosamines, a few of which are suspected as cancer precursors. Thus, the objective of reducing or eliminating nitrite is of great interest to meat researchers and industries. This review, for the first time, discusses the influence of processing technologies such as microwave, irradiation, high-pressure thermal processing (HPTP) and multitarget preservation technology on the quality characteristics of processed meats, with a focus on their sensory quality. These emerging technologies can help in the alleviation of ingoing nitrite or formed nitrosamine contents in meat products. The multitarget preservation technology is an innovative way to enhance the shelf life of meat products through the combined use of different technologies/natural additives. The challenges and opportunities associated with the use of these technologies for processing meat are also reviewed.

KEYWORDS
high-pressure thermal treatment, innovative technologies, irradiation, microwaves, multitarget preservation technology

1 | INTRODUCTION

In recent years, scientific controversies on the use of chemical preservatives, especially nitrites in processed meat products, are posing a challenge for the meat industry. Nitrites are added to meat products as preservatives and antioxidants and to impart flavor and color (Crowe et al., 2019; Pegg & Honikel, 2014). However, nitrites may lead to the formation of carcinogenic N-nitrosamine under some conditions, which has been linked with causing cancer in animals (Cantwell & Elliott, 2017; Crowe et al., 2019; De Mey et al., 2017; Drabik-Markiewicz et al., 2011; Pegg & Shahidi, 2008; Veena & Rashmi, 2014; Virtanen et al., 2019; Xie et al., 2016). Due to changed regulations and increasing consumer awareness, significant research and industrial interest in nitrite-reduction strategies have been noticed (Macho-González et al., 2020; Virtanen et al., 2019). Nevertheless, as nitrite is a multifunctional ingredient, reducing the addition of this additive, while maintaining quality, is a huge challenge for the meat industry (Tobin et al., 2020).

The literature has reported the use of various nitrite and nonnitrite-containing replacers and some innovative technologies to produce low-nitrite or nitrite-free processed meat products. Recent reviews by Munekata et al. (2021) and Ferysiuk and Wójciak (2020) have comprehensively discussed the usage of cruciferous vegetables and plant-based ingredients for replacing nitrite in processed meat products, respectively. The application of high-pressure processing (HPP), cold plasma, with or without added nitrites, can reduce ingoing amounts of nitrites in meat products and has been discussed previously in a recent review by Stoica et al. (2022). This review, for the first time, discusses the effects of novel meat processing technologies, including microwave, irradiation, high-pressure thermal processing and multitarget preservation technology, on the quality and sensory characteristics of processed meat products prepared with low- or no addition of nitrites. The challenges and opportunities associated with these meat processing technologies have also been discussed. The information will be helpful for developing reduced-nitrite or nitrite-free meat products.

2 | MINIMAL PROCESSING TECHNOLOGIES AS NITRITE REDUCTION STRATEGIES

The cured meat products are generally prepared with salt (sodium chloride), nitrite/nitrate, and various other ingredients. These products may be divided into cooked-cured (for example, frankfurters, and luncheon meats) and uncooked (e.g., dry ham and bacon). Generally, microbial safety and of uncooked-cured meat products during the shelf life are ensured by incorporating salt (sodium chloride), nitrite, packaging and refrigerated storage. However, for cooked-cured meat products, stability is based on the incorporation of curing agents, thermal processing treatments, packaging, and storage (Moschopoulou et al., 2019). Some processing conditions can be controlled during cooking/drying/smoking, storage, and packaging to alleviate the use of nitrite or the formation of nitrosamines in meat products (Drabik-Markiewicz et al., 2011). Innovative technologies have been reported to reduce the nitrites/nitrosamines in cooked meat and meat products through different mechanisms (Table 1). Each of these technologies has been discussed in the next sections.

2.1 | Irradiations

A promising alternative technology to replace nitrite without increasing the safety risk is the application of gamma radiation to meat products. It is a nonthermal technology known as the best technology to destroy pathogenic and spoilage microbes in food products (Silva et al., 2021). The literature reported that gamma radiations could induce radiolysis of the nitrite and nitrosamines, thus reducing their concentrations in the product (Dutra et al., 2016). Houser et al. (2003) suggested that oxidative conditions and free radicals produced from irradiation can reduce the activity of the added and endogenous reductants to convert nitrite into nitric oxide. Moreover, this did not seem to affect meat's color either at the beginning or throughout the storage (Houser et al., 2003). This technology can be applied to meat products to reduce microbial growth, reduce concentrations of sodium nitrite, and provide the desired color in red meat products. A recent study by Silva et al. (2021) reported that gamma radiation treatment at 3 kGy, along with 50 mg/kg of nitrite, can be used to ensure microbiological safety and improving the organoleptic characteristics of cooked hams. As per the findings of the study, the number of recovered spores of *Clostridium botulinum* decreased with an increase in the radiation dose. However, the presence of nitrite reduced the spore's resistance to the radiation. Thus, the radiation sensitivity of the *Clostridium sporogenes* spores declined from 1.98 kGy for the uncured sample to 1.81 and 1.57 kGy in cured hams (cured with 50 and 150 mg/kg of sodium nitrite, respectively).

Similarly, Dutra et al. (2011) demonstrated that lower amounts of nitrite (75 ppm) were sufficient to keep the cured color of cooked bologna, even with the high γ-irradiation dose treatment (15 kGy). A little increase in lipid oxidation reaction was noticed with an increase in radiation dose, but there were no remarkable changes in the quality of products prepared with lower amounts of nitrite (Dutra et al., 2011; Sindelar & Milkowski, 2012). However, in their next study, Dutra et al. (2016) investigated the influence of γ-irradiation doses (0, 10, and 20 kGy) on *C. botulinum* (10^7 spores/g) in mortadella prepared with different levels of sodium nitrite (0, 150, and 300 ppm). The results have reported that independent of the concentrations of the sodium nitrite and irradiation/cooking processing order utilized, γ-irradiation treatment alone (more than 10 kGy) enhanced the inactivation of *C. botulinum* in mortadella samples.

The cumulative findings of the above-discussed studies suggested that irradiated and low-nitrite-containing meat products should be considered a healthy and convenient alternative to traditional meat products, which have

TABLE 1 Effects of novel technologies on quality characteristics of meat products

Technology	Conditions	Type of meat products	Effects	References
Microwave	2450 MHz for two times, 45 s and 75 s	Beef cocktail smokies	• Lowest production of the nitrosamines in microwave-treated samples than the pan-frying (171–206°C) and grilling	Mirzazadeh et al. (2021)
	2450 Hz, 700 W for two heating cycles of 2 min	Dry-cured sausages	• Lower (boiling) and indirect heat (microwave) application to dry-cured raw sausages did not affect the nitrosamine content • Higher nitrosamine content in fried sausages may be due to the greater cooking temperature during frying (deep-frying: 150°C for 5 min/side, pan-frying: 150°C for 10 min)	L. Li et al. (2012)
	2450 MHz (600 W) for 1, 2, 3, 4, and 5 min	Minced pork (picadillo) and picadillo-filled tamales	• No detectable counts of *Clostridium perfringens* spores were observed in samples treated with microwave as a reheating treatment	Villarruel-López et al. (2016)
Irradiation	Gamma radiation (3 kGy) and 50 mg/kg of nitrite	Cooked hams	• Recovered spores' numbers of *Clostridium botulinum* decreased with an increase in the radiation dose • *Clostridium sporogenes* spores' radiation sensitivity declined from 1.98 kGy for the uncured sample to 1.81 and 1.57 kGy in cured hams	Silva et al. (2021)
	0, 7.5, and 15 kGy and different concentrations of nitrite 0, 75, and 150 ppm	Bologna sausages	• Increased levels of lipid oxidation (TBARS) and decreased levels of residual nitrite were observed with irradiation treatment • Irradiation had no effect on the color of bologna products prepared with 150 ppm of nitrite	Dutra et al. (2011)
	0–20 kGy of γ-irradiation treatment and 0–300 ppm of nitrite	Mortadella	• Increased irradiation dose enhanced the lipid oxidation and hue color of the meat product • The addition of higher levels of nitrite decreased the lipid oxidation and hue color but increased the redness of mortadella samples	Dutra et al. (2016)

(Continues)

TABLE 1 (Continued)

Technology	Conditions	Type of meat products	Effects	References
	γ-Irradiation (0, 10, and 20 kGy) and nitrite content (0, 150, and 300 ppm)	Mortadella	• γ-Irradiation had a positive effect on the inactivation of *C. botulinum*	Dutra et al. (2016)
	0, 1.5, 3.0, and 4.5 kGy	Cooked turkey breast meat and cured commercially available turkey breast rolls	• Uncured and irradiated turkey was more sensitive to lipid oxidation than the cured-irradiated samples	Feng et al. (2016)
Multitarget preservation technology	Water activity (0.95), pH 5.4, processing temperature (80 ± 1°C); and storage temperature (3–10°C)	Hotdogs	• Similar counts of *C. perfringens* and *C. botulinum* were observed in nitrite (120 ppm) treated and hurdle-treated samples but lower than the control	Jafari and Emam-Djomeh (2007)

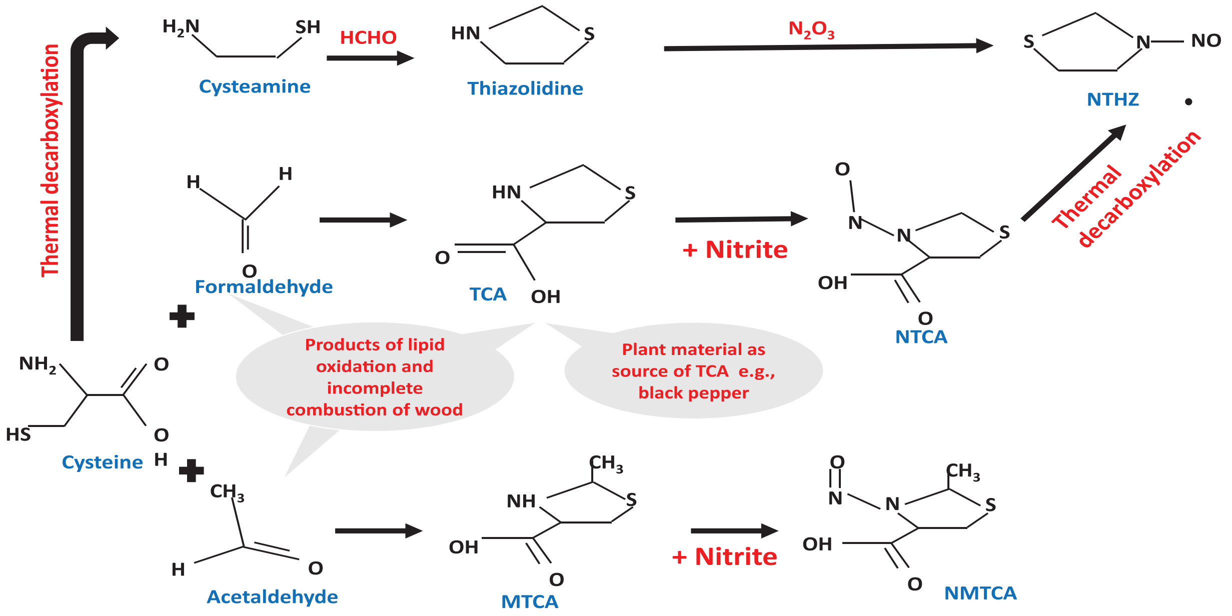
Abbreviation: TBARS, thiobarbituric acid reactive substances.

higher nitrite contents. However, using γ-irradiation on food products can generate free radicals, changes in color, oxidation of lipid, and production of off odors, depending on the irradiation dose and meat type (Feng et al., 2016; Zhao et al., 2017). Feng et al. (2016) documented that uncured-irradiated cooked turkey meat remained more sensitive to lipid oxidation than the cured-irradiated cooked turkey products. The reason could be the absence of nitric acid in uncured samples, which is required to stabilize the myoglobin's iron. Smaller quantities of off-odor volatile compounds were observed in the cured meat samples than in the uncured ones (Feng et al., 2016).

2.2 | Microwaves

The heating treatment with microwave (up to 600 W) can inactivate various types of bacteria such as *Clostridium perfringens*, *Escherichia coli*, *Streptococcus faecalis*, *Staphylococcus aureus*, *Salmonella*, and *Listeria* spp., and spores and bacteriophages as well (Villarruel-López et al., 2016; Woo et al., 2000). As per the study of Villarruel-López et al. (2016), cooked tamales (made with the picadillo [a Mesoamerican dish prepared from the ground pork]) inoculated with 7 logs/g of spores showed no detectable *C. perfringens* spores after microwave as a reheating treatment. However, steaming or frying as a reheating treatment resulted in about 4495 and 255 most probable number (MPN)/g of spores (Villarruel-López et al., 2016).

Other than the microbe's inactivation, microwave cooking can produce lower quantities of volatile nitrosamines than other cooking methods like grilling and pan-frying (Mirzazadeh et al., 2021). The formation of carcinogenic nitrosamine in cured meat products is related to the high internal temperature during cooking and moisture content of the meat product. It has been reported that maximum levels of nitrosamines can occur if meat is heated up to approximately 200°C. Due to the evaporation, heating above that temperature could lead to a reduction in nitrosamine production. The boiling point of nitrosamines such as NPIP, N-nitrosopyrrolidine, N-Nitrosodimethylamine, and N-Nitrosodiethylamine is 217, 214, 154, and 174 (at 721–760 mm Hg). Similarly, a study by L. Li et al. (2012) reported that direct heat treatment such as deep-frying and pan-frying could produce more nitrosamines than raw sausages. However, lower (boiling) and indirect heat (microwave) application to dry-cured raw sausages did not affect the nitrosamine content (L. Li et al., 2012). The reason for lower nitrosamine in boiled sausages than the fried ones could be due to the dissolving of these amines in water (Li et al., 2012). However, higher nitrosamine content in fried sausages may be due to the greater cooking temperature during frying (deep-frying: 150°C for 5 min/side, pan-frying: 150°C for 10 min) than the boiling (90°C for 30 min) and microwave treatment. At higher frying meat temperature, there may be the formation of adducts with unsaturated lipids, which decompose and releases nitrogen oxides and causes nitrosation of free amines, as shown in Figure 1. After nitrosation, there may be a production of thiazolidine-4-carboxylic acid or thiazolidine, which could be further nitrosated (in the presence of residual nitrite or oxides of nitrogen) and result in N-nitrosothiazolidine-4-carboxylic acid (NTCA). The produced NTCA is thermally converted to N-nitrosothiazolidine during cooking at high temperatures, especially during frying, as Tricker and Kubacki (1992) reported. The increased content of various nitrosamines



NTCA: *N*-nitrosothiazolidine-4-carboxylic acid **NMTCA**: *N*-nitroso-2-methyl-thiazolidine-4-carboxylic acid **TCA**: thiazolidine-4-carboxylic acid **MTCA:** 2-methyl-thiazolidine-4-carboxylic acid **NTHZ:** N-nitrosothiazolidine

FIGURE 1 Proposed mechanism for the formation of nitrosamines during meat cooking at high temperatures and in the presence of precursors like black pepper (*Source*: Herrmann et al., 2015; Tricker and Kubacki, 1992)

such as N-nitrososarcosine (NSAR), N-nitrosopiperidine (NPIP), N-nitroso-2-methyl-thiazolidine-4-carboxylic acid (NZMTCA), and NTCA by pan-frying has also been reported by Herrmann et al. (2015).

Due to the reduction of nitrosamine content after microwave treatment, it can be used to produce low-nitrite contained in meat products. Combining this technology with natural preservatives would be an interesting approach in which the synergistic antimicrobial action produced by both technologies may help in the reduction of treatment intensities and input energy needed.

2.3 | High-pressure thermal processing

One of the limitations of high-pressure processing is reduced effectiveness in spore inactivation. As high-pressure thermal processing (HPTP) is a combination of pressure (around 600 MPa) and mild heat treatment (about 80–125°C), it can cover the gap by inactivating the bacterial spores and can produce fresh and extended storage life of meat products, as shown in Table 1 (Tobin et al., 2020). The various studies in the literature have reported the effectiveness of HPTP against spore inactivation. Legan et al. (2008) reported the inactivation of nonproteolytic *C. botulinum* spores (type E) through a commercially viable HPTP process (600 MPa, 90°C for around 3 min) by the standard thermal process at 90°C/10 min (Legan et al., 2008). Likewise, Silva (2016) investigated the combined effect of HPP (600 MPa) and thermal treatment (70°C) for the inactivation of *Bacillus cereus* spores in beef slurry and reported 4.9 log reductions after 20 min treatment time than the 0.5 logs with heat treatment only (70–90°C for 20 min) (Silva, 2016).

Interestingly, HPTP affects the molecules responsible for the color and flavor of the meat less than the heat, consequently preserving the natural color and flavor of the meat products. The benefit of this technology is the reduced requirement for artificial coloring and flavoring materials for meat products (Legan et al., 2008; Tobin et al., 2020).

As a combination of high pressure and heat treatment is used in this technology, it can inactivate microbes and their spores in meat products with a lower influence on their color and flavor characteristics than the heat treatment only. The research studies on this technology are scarce; therefore, future research on implementing this technology as a nitrite replacer can be interesting. Selection of appropriate packaging material to provide protection during the storage life of meat products and to withstand the extreme processing conditions will also be required.

2.4 | Multitarget preservation technology

The stability of uncooked/semicooked cured meat products, especially dry-cured ham, relies on low water activity and usage of nitrite and salt. The combination of various preservation methods, as additional hurdles through different mechanisms, can be an innovative and alluring intervention to ensure the complete safety of uncooked cured meat products. In food processing/ preservation, the most frequently used hurdles are the combined use of pH, water activity, storage temperature, modified atmosphere, and preservatives to alleviate the number of cells and microbial growth. The influence of different hurdles to reduce the use of nitrite by selecting the water activity, acidity, processing, and storage temperature, along with added preservatives in hotdogs, have been investigated by Jafari and Emam-Djomeh (2007). The water activity was adjusted to 0.95 by incorporating humectants (products used to keep products moisturized); acidity was adjusted to pH 5.4 by adding glucono delta-lactone; processing temperature was $80 \pm 1°C$; and storage temperature of 3–10°C. The total aerobic counts in the hurdle-treated samples (a_w = 0.950, F value = 80°C, t values = 3–10°C, 50 ppm nitrites) underwent reduction ($<100 \times 10^3$ colony forming units (CFU)/g) in their initial microbial loads than the control prepared without any preservatives (4×10^5 CFU/g). However, the *C. perfringens* and *C. botulinum* counts remained the same in both samples (hurdle-treated and 120 ppm sodium nitrite-treated samples) but lesser than the control. Moreover, both samples (hurdle-treated and control hotdog samples) obtained the same overall acceptability and organoleptic attributes, which indicates that nitrite should be incorporated into the cured meat products to the lowest extent possible (Jafari & Emam-Djomeh, 2007).

However, the microbes develop resistance mechanisms to these hurdles and preservation methods over the years (Puga et al., 2016; Rosario et al., 2021; Shrestha & Nummer, 2016). For instance, *S. aureus* can survive thermal treatments and again can spoil the meat after cooking (Khalafalla et al., 2019; Roobab et al., 2022). This microbe has become a threat to public health; it can easily adapt to become methicillin-resistant *Staphylococcus aureus* (MRSA), even under selective antimicrobial pressures, thus causing staphylococcal foodborne illness, which may lead to MRSA infection (Ribeiro et al., 2018). This opportunistic microbe can grow in an extensive range of pH, temperatures, and salt (sodium chloride concentrations up to 15%) ranges (Hu et al., 2020; Roobab et al., 2022). To address these concerns, the emerging preservation technologies can be used as an alternative strategy to maintain the quality characteristics of meat products and overcome microbial resistance. Numerous research studies have demonstrated the efficacies of combining novel nonthermal technologies with other preservatives methods/technologies on uncooked/semicooked cured meat products (Akhter et al., 2021; Bragagnolo et al., 2005; Cui et al., 2017; Huq et al., 2015).

2.4.1 | Combination of irradiation with natural preservatives

It has been reported that irradiation up to 10 kGy (for bacteriostatic) and 25 kGy (for bacteriocidal) produces no special changes in the nutritional values of foods, and currently, more than 26 countries are currently utilizing this process commercially (Maherani et al., 2016). However, this treatment is not recommended for high fat-containing foods because, in the presence of oxygen, radiations can accelerate lipid oxidation and produce free radicals and hydrogen peroxide, and destruction of compounds like antioxidants and carboxylic acids (Harder et al., 2016; Lima et al., 2018; Woodside, 2015). Recent research developments have included the combined use of bioactive ingredients to reduce irradiation doses needed for preservation (Abdeldaiem, 2014; Ayari et al., 2016; Hassanzadeh et al., 2017; Xiao et al., 2011). Depending on the added bioactive compounds (essential oils or their bioactive compounds) and combined treatment (mild heat treatment and modified atmospheric packaging), the relative bacterial sensitivity increased 2 to 4-fold and resulted in a decrease in the irradiation dose needed for food preservation (Maherani et al., 2016; Turgis et al., 2008). In research studies, a synergistic effect of medium irradiation doses up to 2–6 kGy and natural bioactive compounds enhance the shelf life of several types of meat products (Abdeldaiem, 2014; Ayari et al., 2016; Hassanzadeh et al., 2017). For instance, Akhter et al. (2021) compared the combined efficacy of low dose γ-irradiation, antimicrobial (sodium nitrate and nisin) and antioxidants (Butylated Hydroxytoluene (BHT) and rosemary) on various quality characteristics of mutton meat emulsions. In nonirradiated mutton meat emulsions, a higher antioxidant effect of BHT against oxidative reactions than the rosemary extracts during processing was reported. However, rosemary extract prevented lipid oxidation similar to BHT in irradiated (1 kGy) meat emulsions, and combinations of nisin and irradiation were effective against microbial spoilage (yeast, mold, and total plate count) similar to irradiated-sodium nitrate-containing samples (Akhter et al., 2021).

In recent years, the combined application of innovative technologies and encapsulated natural antimicrobial/antioxidant agents, which are more stable than the free bioactive, have been reported. Encapsulation is an effective and alluring technique to improve the radiosensitivity of microbes present in foods. A combination of nonmicroencapsulated cinnamon and nisin with γ-irradiation (1.5 kGy) exhibited a 0.17 ln CFU/g/day growth rate of *Listeria monocytogenes* on ready-to-eat pork meat, while the growth rate of microencapsulated cinnamon and nisin with γ-irradiation were 0.03 ln CFU/g/day (Huq et al., 2015). The probable reason for this improvement may be the production of free radicals through radiolysis of water during γ-irradiation treatment, which could decrease the activity of antimicrobial agents in samples containing free antimicrobial agents due to direct exposure to radiations and leading to the loss of their activity. However, for encapsulated bioactives, the free radicals possible degraded the outer materials and not the antimicrobial substances present in the core (Huq et al., 2012).

Although the irradiation process can improve food safety and prolong the shelf life of the food products by reducing microbial growth, the adaption of this technology depends on the country and consumers' understanding. In some cases, a lack of acceptance of this technology due to consumers' misunderstandings may hinder the adaption of this technology (Maherani et al., 2016).

2.4.2 | Combination of cold plasma with natural preservatives

Cold plasma is an ionized gas containing a series of antimicrobial substances like reactive oxygen species, charged particles, electromagnetic fields, UV-C photons, and reactive nitrogen substances (Gavahian & Cullen, 2020). Several studies have reported that cold plasma reduced the counts of pathogenic and spoilage microorganisms in raw and processed meats (Han et al., 2016). Although cold plasma offers various advantages, there are some disadvantages associated with the use of this technology to control foodborne pathogens and spoilage microbes (Hertwig et al., 2017; Surowsky et al., 2016). For instance, regarding the microbial safety of pork jerky inoculated with *S. aureus* and *Bacillus cereus*, a longer time treatment of atmospheric pressure DBD plasma treatment (for 60 min) resulted in less than 1.0 log CFU/g (5–6 log CFU/g initial counts) (Yong et al., 2019). Thereby to obtain effective microbial decontamination, the combined treatment of plasma and safe and antimicrobial substances like essential oils, lactic acid, and bacteriophages have been used (Cui et al., 2018; Matan et al., 2014; Trevisani et al., 2017). The combined use of cold plasma and essential oils has been used to improve meat products' quality and safety characteristics. It has been reported that higher concentrations of lemongrass essential oil (10 mg/ml) for longer treatment time (40 min) and high power cold plasma (600 W) for increased time (180 s) were required to achieve a higher inactivation rate of *L. monocytogenes* when these were used individually. In contrast, a combination of cold plasma (120 s, 500 W) and essential oil (5 mg/ml, 30 min) exerted a synergistic antimicrobial effect on the *L. monocytogenes* (4 log CFU/g) with a decrease of 2.80 logs CFU/g at a reduced concentration of essential oil, cold plasma power and treatment times. Additionally, physicochemical properties (color, TBARS, and texture) and sensory characteristics (off-flavor, appearance, taste, color, and overall acceptability) of pork loin were not affected (Cui et al., 2017). Similarly, the combined use of cold plasma (15 min) and clove essential oil (1%) reduced greater than 7.5 log CFU/g for *Escherichia coli* and 8 log CFU/g for *S. aureus* in beef jerky. However, their individual usage of these technologies showed a lower decrease (3 log CFU/g) of both foodborne pathogens. In addition, cold plasma did not show any effect on the antibacterial efficacy and chemical composition of essential oil, indicating no degradation of essential oil (Yoo et al., 2021).

Undoubtedly, studies regarding the treatment of meat products with plasma are present in the literature abundantly. The effectiveness of this treatment depends on several factors such as microbe's composition and initial levels, cold plasma device, and food type (Min et al., 2016; Roobab et al., 2022).

For industrial purposes, cold plasma treatment is not certified as an antimicrobial technology, so its direct application to unpackaged food meets with obstacles (German Research Community, 2012). For the adaption of in-package cold plasma technology with efficient plasma sources, future studies are required to develop, formulate, and preserve packaged food products (Roh et al., 2020; Roobab et al., 2022). Moreover, sufficient data is unavailable on its mode of action to inactive microbes and increase the shelf life of food products (Roh et al., 2020; Roobab et al., 2022). Future research studies emphasizing a clear understanding of its mechanism of action will help to pave the way for its acceptability in several food treatments and synergistic action in hurdle technologies. Moreover, the safety of consumption of plasma-treated water or foods has not been approved by the governmental authorities yet, thereby needing scientific evidence to ensure its safety.

2.4.3 | HPP and natural preservatives

HPP has been successfully used to inhibit the growth of harmful pathogens such as *L. monocytogenes, E. coli, Salmonella*, and vegetative spoilage microbes such as *Pseudomonas* and LAB, and yeast in various types of meat and meat products (Hugas et al., 2002; Kameník et al., 2015). Numerous studies in the literature documented that HPP could allow limiting the contents of sodium chloride and sodium nitrite in meat products and helps to prolong the shelf life of these reduced salt or nitrate content meat products (Duranton et al., 2012; Omana et al., 2011; Pietrzak et al., 2007). However, HPP can induce lipid oxidation in meat products, depending on the processing conditions and meat type, especially in meat products prepared without nitrites, sulfites, and preservatives containing antioxidant and antimicrobial activity (Bolumar et al., 2016). However, these effects depend on the meat type and conditions and durations of pressure treatment. For instance, pressure treatment of beef samples (at room temperature) increased TBARS values after 7 days of storage at 4°C. However, this increase was more remarkable after pressure treatment at more than 400 MPa (at least fivefold) than the low-pressure treatments (at least threefold) (Ma et al., 2007). Thus, in some studies, combination of low-pressure treatment with natural preservatives to reduce oxidation reactions and microbial growth has been studied. The usage of natural preservatives, either natural antioxidant or antimicrobial agents, can exert a synergistic effect to enhance the shelf life and quality of meat products under lower pressure treatments, as represented in Table 2 (Alahakoon et al., 2015). The synergistic antimicrobial effect of HPP with essential oil or their active compounds, or bacteriocins, affects the cell membrane of microbes, suggesting that the antimicrobials partly damage the bacterial membranes and following pressure treatment results in final inactivation (Pérez-Baltar et al., 2021; Teixeira et al., 2018). For instance, the combined use of carvacrol as a natural phenolic bioactive (at 200 ppm) and HPP (600 MPa for 180 s at 25°C) exerted the desired effect of prolonging the shelf life of low-sodium sliced turkey breast ham. The incorporation of natural hurdle exhibited a remarkable shelf life extension of the product by decreasing the growth rates and maximizing the lag phases of *L. monocytogenes* and other spoilage microbes like lactic acid and psychrotrophic bacteria. During the shelf life period (60 days/4°C), carvacrol remained capable of attenuating the HPP-triggered lipid oxidation in the breast samples (de Oliveira et al., 2015). Similarly, Bragagnolo et al. (2005) reported that HPP (600 MPa for 10 min) led to a remarkable increase in secondary lipid oxidation products in chicken breast samples without rosemary when compared to chicken breast with 0.1% dried rosemary added. During subsequent chilled storage, a slight decrease in secondary lipid oxidation products was detected in the latter (Bragagnolo et al., 2005). Jung et al. (2012) determined the influence of ethanol extracts of garlic, onions, leeks and ginger powder, along with the HPP (0, 300, 450, and 600 MPa) on ground pork against *E. coli* and *L. monocytogenes*. This application of *E. coli* with the garlic extract exhibited the greatest reduction efficiency of 1.86, followed by the leeks, onions, and ginger at 1.25–1.31, 1.17–1.44, and 1.50–1.82, respectively, along with HPP at 450 MPa (Jung et al., 2012). In one investigation, the effect of HPP (300–400 MPa for the time of 15 min) along with the *Melissa officinalis* extract, and their components on the Shiga toxin-producing *E. Coli* in raw ground beef was investigated. The promising results exhibited that properly selected HPP parameters and antimicrobials caused a significant reduction (5-log CFU/g) in *E. coli* and maintained the meat products' quality characteristics (Chien et al., 2019). However, pressure treatment alone caused the 90% reduction in cell counts of *L. monocytogenes*, but treatment with marinades did not cause pressure inactivation of *L. monocytogenes* and *E. coli* in beef, as reported by Li and Gänzle (2016). The research work of Perez-Baltar et al. (2019) reported that combined treatment of HPP (450 MPa for 10 min) and thymol kept the *L. monocytogenes* levels 1.30 and 1.45 log CFU lower than the control samples (without antimicrobials and non-pressurized samples), at 4°C and 12°C, in sliced dry-cured ham. Similarly, the reductions of uropathogenic *E. coli* in ground beef were higher in the combined use of HPP- and citral-treated samples, indicating that citrate increased the *E. coli* inactivation, and thereby the effectiveness of the HPP process increased (Chien et al., 2017). The use of lycopene from tomato byproducts possesses antimicrobial and antioxidant properties, which control oxidative reactions and microbial growth and ameliorate the sensory characteristics of meat products (Amaro-Blanco et al., 2018). The treatment of pork burgers containing tomato pastes with HPP has been reported to increase the shelf life by 1 month with more lipid oxidative stability than the control samples. Additionally, the changes in color by tomato paste and texture values of burgers by the HPP were maintained after cooking. Due to the strong taste of tomato paste, another clean label property of incorporating tomato paste in meat burgers was the reduction of salt content (Amaro-Blanco et al., 2018).

Application of HPP (600 MPa) and the use of sage powder on beef burgers retarded the lipid oxidation throughout the chilled storage of 60 days. Moreover, the microbial quality characteristics of beef burgers were acceptable till the last day of the storage period with and without pressure treatment (Mizi et al., 2019).

Research studies have exhibited that a combination of HPP with additional hurdles like salt or reduced amounts of sodium nitrite can exert a synergistic effect to alleviate the microbial growth and oxidative reactions in meat products. However, the effect of other technologies, ultrasonic and pulsed electric field, which can also exert synergistic action with natural preservatives/reduced amounts of chemical preservatives, must be investigated. Along with this, optimization of the processing conditions and concentration of natural preservatives to exert minimal effects on organoleptic and textural characteristics of meat products is required.

Consequently, novel technologies like HPP and irradiation are needed to produce microbiologically safe meat products with reduced nitrite levels. The application/use of appropriate storage temperature or cold chain break

TABLE 2 Combined uses of innovative technologies and natural preservatives in meat products

Innovative technology	Parameters	Natural preservatives	Concentration	Meat product	Observations	References
Gamma irradiation	1.5 kGy	Microencapsulated oregano, cinnamon, and nisin	250 μg/ml, 250 μg/ml, and 16 μg/ml	Ready-to-eat pork meat	• A combination of nonmicroencapsulated cinnamon and nisin with γ-irradiation (1.5 kGy) exhibited a 0.17 ln CFU/g/day growth rate of *Listeria monocytogenes*, while the growth rate of microencapsulated cinnamon, nisin and irradiation were 0.03 ln CFU/g/day	Huq et al. (2015)
Gamma irradiation	1 kGy	Antimicrobial (sodium nitrate and nisin) and antioxidants (BHT and rosemary)		Mutton meat emulsions	• Rosemary extract prevented lipid oxidation similar to BHT in irradiated (1 kGy) meat emulsions • Combinations of nisin and irradiation were effective against microbial spoilage (yeast, mold and total plate count), similar to irradiated-sodium nitrate-containing samples	Akhter et al. (2021)
Cold plasma	5000–600 W	Lemongrass essential oil	5–10 mg/ml	Pork loin	• A combination of cold plasma (120 s, 500 W) and essential oil (5 mg/ml, 30 min) exerted a synergistic antimicrobial effect on the *L. monocytogenes* (4 log CFU/g) with a decrease of 2.80 logs CFU/g at a reduced concentration of essential oil, cold plasma power and treatment times	Cui et al. (2017)
HPP	300 and 600 MPa	Sage powder	0.3 and 0.6%	Beef burgers	• Lipid oxidation was retarded up to 60 storage days • Microbial quality was acceptable after the 60 days	Mizi et al. (2019)

(Continues)

TABLE 2 (Continued)

Innovative technology	Parameters	Natural preservatives	Concentration	Meat product	Observations	References
HPP	450 MPa for 10 min	Thymol	–	Sliced-dry cured ham	• Combined treatment of HPP (450 MPa for 10 min) and thymol kept the *L. monocytogenes* levels 1.30 and 1.45 log CFU lower than the control samples, at 4°C and 12°C, in sliced-dry cured ham	Perez-Baltar et al. (2019)
HPP	300, 350, and 400 MPa for 15 min	*Melissa officinalis* extracts and chemical constituents	0.5 and 1%	Raw ground beef	• A 3–6 log CFU/g reduction of *Escherichia coli* was observed at 350 and 400 MPa, along with the use of extract and chemical constituents	Chien et al. (2019)
HPP	600 MPa or 450 MPa	Marinade	0.04, 0.025, 0.15, and 0.10 %	Ground beef and marinated beef steaks	• Marinades did not increase the pressure inactivation of *E. coli* in beef steaks and protected the *L. monocytogenes* from sub-lethal injury	Li and Gänzle (2016)
HPP	600 MPa for 10 min	Dried rosemary	0.1%	Chicken breast	• Rosemary attenuated the lipid oxidation in chicken breast	Bragagnolo et al. (2005)
HPP	600 MPa for 180 s at 25°C	Carvacrol	200 ppm	Low-sodium sliced turkey breast ham	• Carvacrol remained capable of attenuating the HPP-triggered lipid oxidation in the breast samples • A decrease was observed in the growth of *L. monocytogenes*, lactic acid bacteria, and psychrotrophic bacteria	de Oliveira et al. (2015)

Abbreviations: HPP, High-pressure processing; BHT, Butylated Hydroxytoluene.

with or without nitrite concentrations is an excellent tool as an additional hurdle to microbial growth, as reported by Redondo-Solano et al. (2013). However, research studies on this topic are scarce in the literature and need further investigation, especially on the optimization of temperature conditions.

Consequently, this combined protection to retard deteriorative mechanisms could help to enhance the shelf life of artificial preservative-free processed meat products, and this entails broadening the logistic opportunities by allowing long-distance distribution in the worldwide market (Bolumar et al., 2016; Mizi et al., 2019). Although the use of multitarget preservation technology looks promising to produce reduced-nitrite or nitrite-free meat products, meat products must contain enough hurdles to prevent the pathogenic and spoilage microbes and oxidative reactions, which is the main target for nitrite additions in meat products. Like high-pressure processing, the use of other technologies could sensitize the cells to the meat environment in which natural preservatives can be added to kill microorganisms.

3 | INCORPORATION OF NOVEL INGREDIENTS OR ANTIOXIDANTS

The usage of natural antimicrobial, antioxidant, and coloring agents to mimic the roles of nitrites through different hurdles in meat products has been reported. Among the natural sources, certain vegetables, including celery, radishes, lettuce, spinach, and so forth, contain nitrates naturally. The literature depicted the potential of their extracts as a promising source of natural nitrates (Jo et al., 2020). To eliminate the direct additive (nitrate/nitrite), the usage of vegetable sources could be advantageous. So far, the most widespread strategy to alleviate the use of conventional nitrite in processed meat products is plant-based extracts or powders (Aquilani et al., 2018). Ruiz-Capillas et al. (2015) used different ingredients to produce nitrite-free hot dogs in order to improve their color (annatto, orange dietary fiber, and cochineal), microbial (lactate), and lipid oxidation stability (vitamins C and E, orange dietary fiber). Celery powder has also been utilized as an ingredient because of the presence of natural nitrates. The hot dogs made up of cochineal obtained better scores in terms of sensory and technological results than annatto-added samples. From the sensory analysis, cochineal-added samples had the virtue of being like nitrite-incorporated sausages. However, no noticeable effect on lipid oxidation stability and microbial growth was reported (Ruiz-Capillas et al., 2015). Similalry, a recent study by Huang et al. (2020) has reported the combined use of different preservatives as a nitrite substitute to produce nonnitrite-added cured meats. This study used *L. fermentum* and *L. plantarum* as starters, beet red and *Monascus* as coloring agents, and nisin as an antibiotic. During the storage period of 20 days at 18–20°C, the resulting product showed better organoleptic characteristics, lower nitrite contents, greater content of free fatty acids and volatile compounds, and more total plate counts but without pathogenic microbe than the control (prepared with only salt) and the sample containing both salt and nitrite (Huang et al., 2020). Šojić et al. (2020) reported that the addition of organic peppermint essential oil (0.075 µl/g) and tomato pomace (0.075 µl/g) increased the quality of the cooked sausages with lower levels of sodium nitrite (Šojić et al., 2020). A combination of nisin, chitosan, or ε-polylysine with a natural antioxidant mixture made up of olive leaves, green tea extracts, or stinging nettle extracts has also been explored as a promising nitrite replacer in frankfurter sausages. Because of the antimicrobial, antioxidant, organoleptic, and technological effects of 0.2 % ε-polylysine and 1% chitosan (in combination with mixed extracts) on sausages throughout refrigerated storage for 45 days at 4°C, a combination of these two were recommended as nitrite replacer (Alirezalu et al., 2019).

Indeed, plant-based alternatives meet the consumer demands for clean-label meat products and help reduce residual nitrite content in meat products. However, various limitations, such as the requirement of starter bacteria to convert nitrate into nitrite (because vegetables are a good source of nitrates); the variability of nitrate content based on the plant source and anatomical part; allergen nature of some vegetables (celery); distinct flavor and pigment profile of the plant extracts pose obstacles for their use in meat products (Ursachi et al., 2020). Notably, the health risk of nitrosamine formation from the nitrites remains as some nitrite is present in meat products, cured using vegetable sources (Flores & Toldrá, 2020). An example is that using vegetable sources with black pepper contributes to the formation of nitrosopiperidine (this formation can be affected by several factors) (De Mey et al., 2017). Consequently, natural sources of nitrite cannot be considered healthier. Therefore, to establish food safety, Food and Drug Admiration (FDA) recommended the need to demonstrate that N-nitrosamines are not formed in curing mixtures (FDA, 2019).

4 | EFFECTS OF THE INNOVATIVE TECHNOLOGIES ON SENSORY CHARACTERISTICS OF MEAT PRODUCTS

The cured color and flavor are the unique characteristics provided by the nitrites to meat products, which the consumer prefers. The application of processing technologies may positively or negatively influence the sensory attributes of meat products.

Consumer research and surveys reported that reduced meat quality has a significant effect on the consumer unacceptability of irradiated meat (Lee et al., 2003). The increased production of off-flavors, lipid oxidation, and color changes is the important quality deleterious changes in irradiated meat (Jin et al., 2012). The possible reason for color changes, particularly decreased redness in meat, maybe the degradation or decomposition of nitrosyl hemochrome or alternation of myoglobin structure by free radicals produced in irradiated meat (Ham et al., 2017; Lee & Song, 2002). The processing of meats with irradiation may initiate or promote lipid oxidation, resulting in associated off-flavors and off-odor products in meat products (Park et al., 2010). Nam et al. (2007) reported that sulfur-containing volatiles could be responsible for producing the off-flavor in irradiated meat, and its production depends on the packaging and storage conditions. Despite the color and aroma alternation in irradiated beef, 2.5 or 5.0 kGy irradiated ham obtained a similar overall acceptance by trained panelists (Jin et al., 2012). However, Park et al. (2010) reported that γ-irradiation treatment up to 10 kGy could reduce the microbial populations without compromising the quality and most of the organoleptic characteristics, including color, taste, and chewiness of meat products. Although the production of off-flavors in both γ- and electron-beam irradiated sausage patties increased continuously, overall acceptance remained unchanged up to 5 kGy treatment (Park et al., 2010). Likewise, the production of more intense sour and cardboardy flavors and sour and salty taste in gamma-irradiated (2 kGy) beef patties than the electron-beam (2 kGy) irradiated patties have been observed by López-González et al. (2000). Byun et al. (2002) documented that the irradiation below 5 kGy did not affect the sensory properties of the ham. The preferable color was observed in the radiation-treated hams prepared with 50 ppm nitrite and without nitrite. The improvements in flavor and texture of hams were noticed using radiation application either with or with no added sodium nitrite (Byun et al., 2002). A recent study by Silva et al. (2021) reported that gamma radiation treatment at 3 kGy, along with 50 mg/kg of nitrite, can be used to ensure microbiological safety and improving the organoleptic characteristics of cooked hams. From the sensory viewpoint, the nitrite had an observable effect on the texture and color of hams, thereby identifying cured samples as different from uncured ham samples (Silva et al., 2021).

Several methods, including the addition of antioxidants, reduced irradiation temperature, and modified atmospheric temperature, can reduce off-flavor production in meat products (Park et al., 2010).

Compared to the conventional cooking method, in which there is a process requirement to transport heat from the source to the product, microwave cooking results in a higher rapid heating rate (Gowen et al., 2006). Meat cooking with microwaves results in faster oxidation and denaturation of myoglobin, followed by the production of ferrihemochrome and color changes from white, brown, and gray (Van Laack et al., 1996). Consequently, these pigments alternations lead to a decrease in lightness (L^*), yellowness (b^*), and redness (a^*) of the meat (S. Li et al., 2019). Interestingly, changes in the thermal properties of collagen (shrinkage, temperatures, and microstructure) during thermal cooking of meat may change the texture or tenderness of the treated meat products. Yarmand et al. (2013) observed higher shear and compression values for microwave-heated camel *longissimus dorsi* muscle than the muscle that had undergone roasting and braising heat treatment, which may be due to the less solubilization of the collagen (Yarmand et al., 2013). Studies on the influence of microwave treatment on the texture-related characteristics of low-nitrite or nitrite-free meat products would also be necessary.

Due to concurrent pressure and denaturation by heat, the high pressure (500 MPa) combined with a mild thermal treatment (53°C) could produce a texture and color comparable to commercial cooked ham (Pingen et al., 2016). Optimization of the suitable conditions to ensure microbial safety would also be required to implement this technology to produce low nitrite or nitrite-free meat products.

5 | CONCLUSIONS AND FUTURE DIRECTIONS

The processing technologies like microwave, irradiation, high-pressure thermal processing, and multitarget preservation technology can help to reduce amounts of nitrite added to meat products due to their antimicrobial activity against food spoilage and pathogenic microbes. Some of these technologies can generate reactive free radicals that change the product color, oxidize lipids, and produce off-odors, but this limitation can be overcome by using low processing doses or in combination with natural antioxidants/antimicrobials. Optimization of the appropriate processing conditions would be needed to implement these technologies, as very few research studies in the literature are available on this topic. The application of combined use of pressure and heat treatment could improve the texture and color of cooked meat products. Meat cooking at a high temperature for more extended period results in higher N-nitrosamine production than low-temperature cooking. Microwave cooking could reduce nitrosamine content in meat products and provide microbial safety by inactivating pathogenic and spoilage microbes. Microwave treatment may be used in the preparation of cooked-cured meat products.

Multi-target preservation technology and natural antioxidants/additives to replace nitrite in meat products are of utmost interest because of the increased demand for reduced or nitrite-free meat products. However, limited data are available on these combined hurdles. With this technology, very low levels of conventional or natural nitrites would be required to be added to the meat products along with other ingredients, natural antimicrobials, antioxidants, color, and flavoring ingredients.

The sustainability aspect of using ingredients or innovative technologies (as nitrite-replacing strategies) requires a fine balance between human health and economic concerns. Taking consideration into the financial impact of replacing the conventional sodium nitrite with other ingredients/technologies, an ante and postcomplementary economic analysis is required to offer clean-label meat products to consumers.

ACKNOWLEDGMENTS

The authors are thankful to Massey University for funding the study.

Open access publishing facilitated by Massey University, as part of the Wiley - Massey University agreement via the Council of Australian University Librarians.

AUTHOR CONTRIBUTIONS

Ramandeep Kaur: conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; validation; visualization; writing – original draft; writing – review & editing. **Lovedeep Kaur**: conceptualization; funding acquisition; project administration; resources; supervision; validation; visualization; writing – review & editing. **Tanushree Gupta**: supervision, visualisation, validation, writing – review & editing. **Jaspreet Singh**: supervision; validation; visualization; writing – review & editing. **John E. Bronlund**: supervision; visualization.

CONFLICT OF INTEREST

The authors have no conflict of interest to declare.

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How to cite this article: Kaur, R., Kaur, L. L., Gupta, T. B., Singh, J., & Bronlund, J. (2022). Multitarget preservation technologies for chemical-free sustainable meat processing. *Journal of Food Science*, *87,* 4312–4328. https://doi.org/10.1111/1750-3841.16329