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Review Paper

Mild technologies in meat processing: balancing nutritional quality and safety

Dragan Vasilev[1*], *Mirjana Dimitrijević*[1], *Ivana Klun*[2], *Aleksandra Uzelac*[2], *Nikola Betić*[3], *Branko Suvajdžić*[1] *and Neđeljko Karabasil*[1]

[1] *University of Belgrade, Faculty of Veterinary Medicine, Bulevar oslobodjenja 18, 11000 Belgrade, Serbia*
[2] *University of Belgrade, Institute for Medical Research, Bulevar oslobodjenja 18, 11000 Belgrade, Serbia*
[3] *Institute of Meat Hygiene and Technology, Kaćanskog 13, 11000 Belgrade, Serbia*

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ABSTRACT

This paper discusses the application of mild processing technologies in the meat industry, with emphasis on their role in preserving nutritional quality and ensuring product safety. Given the highly perishable nature of meat, conventional processing techniques, such as chilling, freezing, curing, smoking, drying and heat treatment, have been employed to extend its shelf life. However, these approaches, especially thermal processing, often compromise sensitive nutrients. In response, optimization of conventional methods, hurdle system application, as well as modern non-thermal and low-intensity technologies, including high-pressure processing (HPP), pulsed electric fields (PEF), ultrasound, and cold plasma, have been developed as effective alternatives. These methods achieve microbial inactivation while minimizing nutritional and sensory degradation. Furthermore, the combination of mild technologies with optimized conventional methods (e.g., sous-vide cooking, vacuum drying, modified atmosphere packaging, biopreservation etc.) has demonstrated synergistic effects in enhancing product quality and satisfying shelf life. This integrated approach supports the production of clean-label, minimally processed meat products that align with contemporary consumer expectations. The findings underscore the potential of mild technologies to contribute significantly to the future of meat processing through improved product safety, functionality, and nutritional retention.

1. Introduction

Meat is a highly nutritious food, valued for its rich content of high-quality proteins, essential amino acids, vitamins (especially B-complex), and bioavailable minerals such as iron and zinc (*Toldrá et al*., 2012). However, due to its high water activity and nutrient density, meat is also highly perishable and susceptible to microbial spoilage as well as enzymatic and oxidative deterioration (*Zhou et al*., 2010). Traditionally, to extend shelf life and ensure safety, a range of processing methods, such as chilling, freezing, curing, drying, smoking and heat treatment, have been developed (*Feiner,* 2006). While effective, many of these conventional techniques, and especially heat treatment, often lead to degradation of sensitive nutrients, sensory changes, and even to the formation of undesirable compounds, such as heterocyclic aromatic amines and others (*Leroy et al*., 2023).

***Corresponding author:** Dragan Vasilev, *vasilevd@vet.bg.ac.rs*

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In response to the growing consumer demand for minimally processed foods with preserved nutrients, the food industry and researchers have developed a range of mild or non-thermal preservation technologies. These include high-pressure processing (HPP), pulsed electric fields (PEF), ultrasound, cold plasma, and others, which aim to inactivate spoilage and pathogenic microorganisms without the use of excessive heat (*Campus*, 2010; *Barba et al.*, 2018). The main advantage of these approaches lies in their ability to maintain the nutritional and sensory integrity of the product while ensuring microbial safety (*Bolumar et al.*, 2020).

Moreover, conventional processing techniques in meat industry consume a lot of energy, while innovative solutions, including mild heat treatment and non-thermal methods, offer significant potential to lower energy use, reduce production costs and enhance the overall sustainability of food production (*Selvaraj et al.*, 2025). Thus, mild technologies in meat processing represent a modern solution to challenges of preserving food quality and ensuring safety, while also offering potential for sustainable production (*Ahmed et al.*, 2023).

2. Optimization of conventional processing methods

In the meat processing industry, the greatest loss of nutrients is certainly in sterilized canned meat, but nevertheless, it is necessary to avoid any further excessive loss of the already compromised nutritional value of such products. Namely, the sterilisation process should guarantee that *Clostridium botulinum* spores are destroyed and the manufacturers, aware of the risks involved in such production, often sterilize products too intensively. Testing the F_0-value in several facilities, although $F_0 \geq 3$ is needed to ensure safety, values of more than 8, in some cases even over 10 were determined (*Vasilev et al.*, 2019). Such values are unnecessarily high from a safety perspective, but also significantly reduce the nutritional value of the product and unnecessarily waste energy resources (*Vasilev et al.*, 2019). Simple optimization of the existing heat treatment procedures according to the F_0 value, a very useful tool in assessing the microbial lethality obtained during the heat treatment, can contribute not only to the better preservation of products nutritional value but also to savings in facility energy consumption (*Rašeta et al.*, 2018).

In contrast to sterilized cans, from the nutritive and safety point of view, much more attention is paid to combining mild thermal treatments with other preservation strategies. Traditional processes such as heat treatment, drying, smoking and fermentation can be adapted using lower temperatures or shorter processing times to reduce nutrient loss while still achieving desirable preservation effects (*Toldrá et al.*, 2012). This approach, well known as *hurdle technology*, represents the simultaneous action of several antimicrobial parameters (F-, pH-, water activity (a_w-)value, biopreservation, etc.), thanks to which it is possible to achieve adequate product safety even though milder conservation procedures are used, and is a good path to enhance both shelf life and nutritional integrity (*Leistner & Gould*, 2002).

For example, mild heat treatments (e.g., pasteurization at 55–65°C) can be combined with vacuum drying or modified atmosphere packaging (MAP) to inhibit microbial growth and oxidative degradation, while minimizing thermal damage to heat-sensitive nutrients, such as thiamine and vitamin B12 (*Zhou et al.*, 2010). Similarly, sous-vide cooking, which is typically done at 55–65 °C for extended time followed by chilling and vacuum packaging, preserves meat texture and nutritional quality more effectively than conventional cooking (*Roldán et al.*, 2013). In fermented and cured meat products, relatively low concentrations of salt and nitrites are being used in combination with bioprotective cultures and controlled drying to maintain safety while aligning with clean label demands (*Toldrá & Reig*, 2011). Mild heat treatment in combination with previous marinating and mild smoking, with additional short drying, contributes to producing a product without the use of chemical preservatives and flavour enhancers, which is aromatic and nutritionally satisfactory, but also safe due to the adjusted F- and a_w-value (*Vasilev et al.*, 2025). Similarly, essential oils (e.g., citral) combined with sublethal heat (53°C) have demonstrated synergistic *Escherichia coli* O157:H7 inactivation in meat model systems, indicating potential for lower thermal loads and improved nutrient retention (*Berdejo et al.*, 2023). Finally, the whole group of so-called *refrigerated processed foods of extended durability* has been developed, which are focused on mild heat, preserved nutritive value, but also extended shelf life (*Vasilev et al.*, 2019). These combinations illustrate how classical techniques can be re-engineered with milder parameters, but also they could be combined with emerging technologies to meet modern standards of quality, nutrition, and safety, which is described in the following section.

3. Emerging non-thermal technologies in meat processing

Several non-thermal technologies have been developed and studied for their ability to ensure microbial safety while preserving the nutritional and sensory attributes of meat products.

High-pressure processing (HPP) is one of the most extensively researched non-thermal technologies. It involves the application of pressures up to 600 MPa, which can effectively inactivate pathogenic and spoilage microorganisms without significantly raising the temperature of the product (*Campus*, 2010). HPP-treated meat retains its natural colour, texture and nutrient profile better than thermally processed counterparts (*Bolumar et al*., 2020).

Pulsed electric fields (PEF) apply short bursts of high voltage to food placed between two electrodes. This method permeabilizes microbial cell membranes, leading to cell death, with minimal thermal impact. PEF has shown promising results in improving tenderness in meat and accelerating marination, all while preserving vitamins and other heat-sensitive compounds (*Toepfl et al*., 2006).

Pulsed light (PL) uses short, high-intensity flashes, mainly in the UV spectrum, to inactivate microorganisms by damaging their DNA. In the meat industry, PL can decontaminate carcasses, knives, sliced fermented sausages, and improve the safety of fresh products like beef or tuna carpaccio. However, excessive intensity can alter meat's colour and aroma, so treatment conditions must be carefully optimized (*Mahendran et. al*., 2019).

Ultrasound involves the use of high-frequency sound waves to create cavitation in meat systems, disrupting microbial cells and enhancing mass transfer processes like marination and tenderization. Even more, low-intensity ultrasound has been found to improve meat texture without adverse effects on nutritional value (*Chemat et al*., 2011).

Cold plasma technology relies on ionized gas at room temperature to generate reactive species that inactivate microorganisms on meat surfaces. It is particularly useful for surface decontamination, with minimal impact on product quality. Though still under development for commercial use in meat processing, cold plasma has shown great potential for ready-to-eat products. Many cold plasma systems are suitable for food applications; however, its toxicity requires further study, and regulatory aspects remain obstacles to its adoption in the food sector (*Laroque et al*., 2022).

Ozonation offers several advantages, including cost-effectiveness, the absence of chemicals, environmental friendliness, and ease of use. Nevertheless, its application in the meat industry presents challenges due to ozone's strong oxidative capacity, which can potentially damage cellular fatty acids and proteins in meat (*Roobab et al*, 2024).

Irradiation uses ionizing radiation (gamma rays, electron beams, or X-rays) to improve food safety, extend shelf life, and keep product quality. The absorbed dose is measured in Greys (Gy). When properly applied, irradiation is effective, cold, penetrative, and does not compromise food's sensory or nutritional qualities, although lipid oxidation in fatty foods could be an issue. Irradiation is now used commercially in about 30% of countries worldwide, especially for spices, grains, fruits, vegetables, and to a lesser extent meats and seafood. Wider adoption is limited by consumer acceptance, which could be improved through education and clear labelling (*Vasilev et al*., 2019).

Table 1 provides a comparative overview of conventional, mild, and emerging non-thermal technologies in meat processing, highlighting their main advantages and limitations.

Collectively, non-thermal mild technologies offer promising alternatives to conventional heat-based methods, aligning with consumer preferences for cleaner labels, fresher-tasting products, and preserved nutritional value (*Barba et al*., 2018). As mild heat is often insufficient on its own to inactivate resistant pathogens or spores, non-thermal hurdles, such as high-pressure processing, antimicrobial packaging, cold plasma or natural antimicrobials, can be effectively integrated to achieve substantial microbial inactivation while minimizing physicochemical degradation. HPP paired with vacuum packaging can be used to eliminate pathogens and spoilage organisms while keeping the nutritional value and freshness of raw or lightly processed meats intact (*Campus*, 2010; *Bolumar et al*., 2020). High-pressure thermal processing (HPTP), which applies HPP at pasteurization temperatures (~600 MPa, 70 °C), has been shown to inactivate *Bacillus cereus* spores in cooked and fermented sausages while preserving sensory and nutritional quality (*Kaur et al*., 2022). Similarly, the application of HPP at refrigeration temperatures to dry-cured Iberian ham significantly reduced microbial loads without adverse effects on colour stability or lipid oxidation, maintaining the characteristic attributes valued in such premium products (*Carrapiso et al*., 2023).

Beyond pressure-based approaches, combinations such as cold plasma with HPP offer complementary modes of action, achieving 2–5 log reductions in pathogens across various ready-to-eat meats while preserving vitamins, pigments, and lipid profiles (*Zhang et al*., 2025).

Table 1. Mild and non-thermal technologies in meat processing

Technology	Pros	Cons
Optimized heat treatment	Preserves nutrients; Saves energy; Safe if controlled.	Needs precise monitoring; Risk if under-processed.
Hurdle technology	Synergistic safety; Mild processing; Clean-label potential.	Complex design; Product-specific; Higher cost.
Sous-vide cooking	Good texture and flavour, Less nutrient loss; Longer shelf life.	Long cooking; Strict cold chain.
Modified atmosphere packaging	Slows microbes and oxidation; Extends shelf life.	Needs special gases and materials; Fails if cold chain breaks.
Vacuum drying	Less oxidation; Less nutrient loss; Energy-efficient.	Costly; Not for all meat types.
Biopreservation	Natural; Fewer artificial additives; Clean-label friendly.	Variable effect; Can change taste; Regulatory limits.
High-pressure processing	Kills microbes without heat; Keeps nutrients and texture.	Expensive; Weak on spores; Batch process.
High-pressure thermal processing	Inactivates spores; Preserves quality.	Costly; Limited use.
Pulsed electric field	Low-heat antimicrobial effect; Keeps vitamins; Improves tenderness.	Poor penetration in solids; Scaling issues.
Pulsed light	Fast surface decontamination; No chemicals.	Can alter colour/flavour; Only surface action.
Ultrasound	Improves marination and tenderness; Little nutrient loss.	High power harms texture; Uneven effect.
Cold plasma	Strong surface decontamination; Eco-friendly; Preserves nutrients and pigments.	Surface only; Safety and regulatory concerns.
Ozonation	Cheap; Eco-friendly; Chemical-free.	Oxidizes fats/proteins; Needs strict control.
Irradiation	Effective, penetrative; Preserves nutrients if optimized.	Consumer stigma; Lipid oxidation risk.

4. Conclusion

Mild technologies in meat processing represent a significant advancement toward producing safer, nutritionally superior, and consumer-friendly meat products. By minimizing heat exposure and combining modern non-thermal approaches with optimized traditional techniques, processors can enhance product shelf life and safety while preserving valuable nutrients. Careful selection and optimization of mild thermal processing within a multi-hurdle framework can achieve regulatory safety targets while sustaining the nutritional and sensory qualities of processed meats. The success of such approaches depends on the compatibility of hurdles with the product matrix, the nature of target microorganisms, and the desired shelf life, making process validation essential for each application. Ongoing research and innovation could further refine these methods, ensuring they remain sustainable, effective, and widely applicable.

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Authors info

Dragan Vasilev, https://orcid.org/0000-0002-4066-5731
Mirjana Dimitrijević, https://orcid.org/0000-0003-1670-6481
Ivana Klun, https://orcid.org/0000-0001-7976-3104
Aleksandra Uzelac, https://orcid.org/0000-0002-1424-0123
Nikola Betić, https://orcid.org/0000-0002-7375-6752
Branko Suvajdžić, https://orcid.org/0000-0002-7161-104X
Neđeljko Karabasil, https://orcid.org/0000-0001-6097-3216