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GREEN PROCESSING TECHNOLOGY OF MEAT AND MEAT PRODUCTS: A REVIEW

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Abstract
Green processing technologies are revolutionizing the meat industry by addressing the environmental and health challenges associated with traditional meat processing methods. This review explores several novel green technologies, including high-pressure processing (HPP), cold plasma, ultrasound, pulsed electric field (PEF) processing, and fermentation. These technologies offer significant improvements in terms of energy efficiency, waste reduction, and reduction of chemical additives. This review examines their operational principles, current research findings, and emerging applications. Additionally, the review highlights the integration of these technologies, their environmental impact, economic feasibility, and regulatory landscape. The findings suggest that while green technologies hold substantial promise for enhancing sustainability in meat processing, further research and industry adoption are necessary to fully realize their potential.

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Introduction

Green processing technology refers to a suite of innovative and sustainable methods aimed at minimizing the environmental impact of food production, including meat processing [1]. These technologies are designed to reduce energy consumption, decrease waste, and limit the use of harmful chemical additives while maintaining or even enhancing the quality and safety of food products [2]. In the meat industry, which is often scrutinized for its environmental footprint and resource intensity, green processing technologies are becoming crucial as the sector seeks to align with broader sustainability goals [3].

Traditional meat processing methods such as curing, smoking, and the use of synthetic preservatives have long been the mainstay of the industry [4]. These techniques serve to ensure food safety, extend shelf life, and enhance the flavor of meat products [5]. However, they come with significant drawbacks. The reliance on chemical preservatives not only poses potential health risks to consumers, such as increased exposure to carcinogenic compounds and allergens, but also contributes to substantial environmental challenges [6]. Traditional methods often require high energy inputs, leading to increased greenhouse gas emissions and considerable waste generation [7]. These environmental impacts contribute to climate change and environmental degradation, underscoring the need for more sustainable alternatives.

The push towards green processing technologies is driven by the dual goals of mitigating environmental impact and responding to consumer demand for safer, healthier, and more sustainable food options [8]. Consumers are increasingly aware of and concerned about the environmental and health implications of their food choices, prompting a shift towards products and practices that align with sustainability and health-conscious principles [9]. In this context, green processing technologies offer promising solutions to the challenges faced by traditional meat processing methods [10].

Emerging green technologies such as high-pressure processing (HPP), cold plasma, ultrasound, and pulsed electric fields (PEF) are at the forefront of this shift [11]. High-pressure processing is known for its ability to extend the shelf life of meat products while preserving their nutritional quality and sensory attributes [12]. Cold plasma technology offers an innovative approach to decontaminating meat surfaces, reducing microbial load without the need for chemical agents [13]. Ultrasound technology enhances meat tenderness and marination, while pulsed electric fields improve microbial safety and reduce energy consumption [14,15]. Additionally, fermentation represents a significant advancement in green processing, leveraging natural microbial processes to improve food safety and extend shelf life without relying on synthetic additives [16].

The integration of these technologies into meat processing not only addresses environmental and health concerns but also aligns with evolving industry standards and consumer expectations [17]. By incorporating green processing technologies, the meat industry can reduce its ecological footprint, enhance product safety, and offer more sustainable options to consumers [18]. This shift is not merely a trend but a fundamental change driven by both regulatory pressures and market demands.

The aim of this review is to provide a comprehensive examination of these novel green technologies in meat processing. By evaluating the mechanisms, benefits, and limitations of each technology, this review seeks to highlight their potential to offer sustainable alternatives to traditional meat processing methods. The review will also explore the role of fermentation as an emerging technology, emphasizing its contributions to sustainability and health in the meat industry. Through this detailed analysis, the review aims to outline the current state of green meat processing technologies, assess their impact on food safety, nutritional quality, and environmental sustainability, and identify future directions for research and development in this evolving field.

Objects and methods

This review aims to provide a comprehensive analysis of green processing technologies in the meat industry, specifically focusing on HPP, cold plasma, ultrasound, PEF, and fermentation. The goal is to evaluate an impact of these technologies on sustainability, energy efficiency, waste reduction, and their effectiveness in enhancing meat quality and safety. A systematic literature review was conducted using academic databases such as PubMed, ScienceDirect, and Google Scholar to identify relevant research articles, reviews, and case studies published within the past 14 years. Data were collected on operational principles, applications, energy efficiency, environmental impact, economic feasibility, and regulatory considerations of each technology. Subsequently, a comparative analysis was performed, examining the environmental benefits, cost-effectiveness, and meat quality and safety outcomes associated with each technology.

Inclusion criteria were as follows:

1. Published literature: peer-reviewed articles, conference proceedings, and reviews published within the last 14 years.
2. Relevance to green processing: studies directly discussing HPP, cold plasma, ultrasound, PEF processing, and fermentation in the context of meat processing.
3. Sustainability and environmental impact: research articles evaluating environmental, economic, and health impacts of these technologies.
4. Language: studies published in English.

Exclusion criteria were as follows:

1. Non-relevant processing methods: studies focused on conventional processing methods without integrating green technologies.
2. Irrelevant product types: studies not focused on meat and meat products (e. g., studies on dairy or plant-based products).
3. Insufficient data on sustainability: studies lacking substantial discussion on sustainability metrics or environmental impact.
4. Publications that are purely theoretical or do not include experimental data with practical application

Data sources and geographic information:

The data for this review were primarily sourced from peer-reviewed journals, industry reports, and case studies. Governmental and non-governmental reports on food processing technologies and sustainability, published by organizations such as the FAO, WHO, and Codex Alimentarius Commission, were also included to provide broader insights and regulatory context.

Geographically, the review encompasses studies and data from multiple regions, with a primary focus on research conducted in North America, Europe, and Asia, where green processing technologies have seen significant development and application. Studies from the United States, Canada, South Korea, and China were particularly emphasized due to their advancements in food technology and regulatory frameworks promoting sustainable practices. Where available, comparative data from emerging economies in South America and Africa were also examined to provide a global perspective on feasibility, application, and challenges of green processing technologies.

Research subjects and analysis techniques:

The reviewed studies cover various meat types, including poultry, beef, and fish, treated with green processing technologies. Key parameters include consumer safety, meat quality, and sustainability metrics. The analysis techniques encompass several domains, including environmental impact assessment, which uses methods such as Life Cycle Assessment (LCA) to evaluate energy consumption, emissions, and waste reduction; quality assessment through texture analysis, microbial analysis, and chemical profiling to determine meat quality and safety post-treatment; economic feasibility analysis, involving cost-benefit assessments and case studies of green technology implementation in industrial contexts; and regulatory analysis, evaluating the current regulatory frameworks surrounding these technologies based on guidelines from organizations such as the FDA, EFSA, and Codex Alimentarius Commission. This approach aims to determine the efficacy and potential for industry adoption of each technology.

Overview of traditional meat processing techniques

Traditional meat processing techniques, such as curing, smoking, and the use of chemical preservatives, have long been employed to extend the shelf life of meat products, enhance flavor, and ensure food safety [19,20]. These methods have been effective in preventing spoilage and controlling pathogenic microorganisms, but they come with significant environmental and public health concerns [21,22].

Curing involves treating meat with a combination of salt, nitrates, nitrites, sugar, and spices to preserve it [23]. This process inhibits the growth of spoilage bacteria and pathogens, such as *Clostridium botulinum*, by reducing water activity and introducing chemical preservatives [24]. However, curing relies heavily on nitrates and nitrites, which can react with amines in meat to form nitrosamines — compounds that have been linked to an increased risk of cancer [25]. Additionally, the production and transportation of these curing agents contribute to environmental degradation, including water pollution and greenhouse gas emissions [26].

Smoking is another traditional method that involves exposing meat to smoke from burning wood or other plant materials [27,28]. The smoke imparts flavor, reduces water activity, and introduces antimicrobial compounds, making it an effective preservation technique [29]. However, smoking meat releases polycyclic aromatic hydrocarbons (PAHs), which are known to be carcinogenic [30]. Furthermore, the energy required for smoking, along with the consumption of wood, contributes to deforestation and air pollution, raising concerns about the sustainability of this practice [31].

The use of chemical preservatives, such as sodium benzoate, potassium sorbate, and sulfur dioxide, is common in the meat industry to inhibit microbial growth and prolong shelf life [32]. While these chemicals are effective, they can pose health risks, including allergic reactions and potential toxicity with long-term exposure [33]. There is also a growing consumer demand for clean-label products with fewer synthetic additives, challenging the meat industry to find safer and more natural alternatives.

Despite their effectiveness, traditional meat processing methods have several limitations, particularly concerning environmental sustainability [34]. Many of these methods rely on non-renewable resources and produce substantial waste, contributing to pollution and climate change [35]. For example, the use of chemical preservatives involves the production of synthetic chemicals, which generates harmful by-products and waste [36]. Smoking processes, requiring large amounts of wood and emitting significant amounts of smoke, lead to deforestation and increased carbon emissions, further exacerbating environmental damage [37].

Another major limitation is the high energy consumption associated with traditional processing techniques. Smoking meat requires constant heat, which consumes a significant amount of energy [38]. Curing processes often need refrigeration over extended periods, increasing energy demands [39]. This high energy usage not only elevates operational costs but also contributes to the overall carbon footprint of the meat industry [40], making it less sustainable in a world increasingly focused on reducing energy consumption and greenhouse gas emissions [41].

Therefore, while traditional meat processing methods have been essential for ensuring the safety and longevity of meat products, their environmental impact, high energy consumption, and associated health risks underscore the need for more sustainable and health-conscious alternatives. The meat industry must explore and adopt novel green processing technologies to reduce its ecological footprint and meet evolving consumer demands.

Green processing technologies: a novel approach

Green processing technologies in meat production refer to innovative methods that aim to minimize the environmental impact of processing while maintaining or enhancing the safety, quality, and nutritional value of meat products [42]. These technologies focus on reducing energy consumption, minimizing waste, and avoiding harmful chemical additives [43]. The goal of green processing is to create a more sustainable meat production system that aligns with the growing demand for environmentally friendly and health-conscious food products [44].

Energy efficiency is a core principle of green processing technologies [45]. Unlike traditional methods, which often require significant amounts of energy for processes such as heating, cooling, and drying, green technologies aim to use less energy through advanced methods and equipment [46]. For example, technologies such as HPP and PEF can achieve microbial inactivation and extend shelf life without the need for high temperatures, thus saving energy [47,48]. This reduction in energy use not only lowers the carbon footprint of meat production but also reduces operational costs, making it a more sustainable and economically viable option for the meat industry [49].

Waste minimization is another fundamental principle of green processing technologies [50]. Traditional meat processing often generates substantial waste, including organic by-products and packaging materials that contribute to environmental pollution [51]. Green processing technologies seek to minimize this waste through techniques that optimize resource use and reduce by-products [52]. For instance, membrane filtration technologies can recover valuable proteins and other components from processing wastewater, turning what was once waste into useful ingredients [53]. Additionally, the use of biodegradable or recyclable packaging materials further reduces the environmental impact of meat production, aligning with circular economy principles [54].

Reduction of chemical additives is a key objective in the application of green processing technologies [55]. Conventional methods often rely on chemical preservatives and additives to ensure product safety and extend shelf life, which can pose health risks to consumers and contribute to environmental pollution [56]. Green technologies aim to replace these synthetic chemicals with natural alternatives or physical processes that achieve the same goals without the associated risks [57]. For example, cold plasma treatment and ultraviolet (UV) light are non-thermal methods that can effectively inactivate pathogens on meat surfaces without the need for chemical additives [58]. By reducing reliance on chemicals, these technologies not only enhance food safety but also meet consumer demand for "clean-label" products with fewer artificial ingredients.

Finally, green processing technologies offer a novel approach to meat production by prioritizing energy efficiency, waste minimization, and the reduction of chemical additives. These principles help create a more sustainable, health-conscious, and economically viable meat industry that is better aligned with environmental goals and consumer expectations.

Emerging green processing technologies

Emerging green processing technologies are revolutionizing the meat industry by providing sustainable alternatives to traditional methods [59]. These technologies not only enhance food safety and quality but also reduce environmental impact and minimize the use of chemical additives [60]. Below is an overview of some of the most promising green processing technologies currently being explored in meat production (Table 1).

HPP is a non-thermal preservation method that inactivates microorganisms by applying extremely high pressure (up to 600 MPa) to meat products [61]. This process disrupts microbial cell membranes and proteins, effectively eliminating pathogens and spoilage organisms without the need for heat [62]. HPP is used for a variety of applications, including extending shelf life, maintaining fresh-like quality, and enhancing safety in ready-to-eat meat products [63].

One of the main benefits of HPP is its ability to retain nutrients, flavors, and sensory attributes of meat because it does not involve high temperatures, which can degrade heat-sensitive compounds [64]. Additionally, HPP reduces the need for chemical preservatives, aligning with consumer demand for cleaner labels and more natural products [65]. Recent research has focused on optimizing pressure levels and treatment times to maximize microbial inactivation while preserving the quality of meat [66,67]. Innovations include the development of HPP-compatible packaging materials and the integration of HPP with other mild preservation methods to further enhance safety and quality [68].

Cold plasma technology is an emerging non-thermal method that generates reactive gas species at low temperatures to decontaminate meat surfaces [69]. This technology works by exposing meat to ionized gas, which produces reactive oxygen and nitrogen species capable of inactivating a broad spectrum of microorganisms, including bacteria, viruses, and molds [70]. Cold plasma is particularly effective in reducing surface contamination without affecting the core temperature or quality of meat [71].

Compared to conventional decontamination methods, such as chemical washes or heat treatments, cold plasma offers several advantages. It requires no water or chemical additives, thus minimizing waste and avoiding chemical residues on meat products [72]. Moreover, the process is energy-efficient and can be applied in real-time during meat processing, reducing the need for additional handling or storage [73]. Recent advancements in cold plasma technology have focused on developing scalable systems for commercial meat processing and optimizing the plasma parameters for different types of meat products [74].

Ultrasound technology uses high-frequency sound waves to create cavitation bubbles in liquid environments, which implode and generate localized high temperatures and pressures [75]. In meat processing, ultrasound is used to tenderize meat by breaking down muscle fibers and connective tissues and enhancing marination by increasing the penetration of marinades into meat [76]. This technology can significantly improve the texture and flavor of meat products without the need for extended marination times or mechanical tenderization [77].

Ultrasound technology also offers environmental benefits, such as reduced water and energy usage compared to traditional methods [78]. It can be integrated into existing processing lines with minimal modifications, making it a cost-effective option for meat processors [79]. Recent advancements in ultrasound technology include the development of low-frequency systems that minimize heat generation while maximizing the tenderizing effects, as well as combined ultrasound treatments with other non-thermal technologies to further enhance meat quality and safety [80,81].

PEF processing involves the application of short bursts of high-voltage electric fields to meat products, which disrupts cell membranes and inactivates microorganisms [82]. PEF is primarily used to enhance microbial safety in meat by effectively reducing the load of pathogens such as *Escherichia coli* (*E. coli*), *Listeria monocytogenes* (*L. monocytogens)*, and *Salmonella* species [83]. The technology can also improve the extraction of intracellular compounds, such as proteins and flavors, contributing to the enhancement of meat quality [84].

PEF processing has minimal effects on meat quality, as it operates at low temperatures, preserving the sensory and nutritional attributes of the product [85]. Additionally, PEF is energy-efficient, as it requires less energy compared to thermal pasteurization methods [86]. Current research is exploring the synergistic effects of PEF when combined with other preservation technologies, such as HPP and cold plasma, to enhance microbial inactivation while maintaining product quality [87,88].

Fermentation and bio-preservation utilize natural fermentative microbes and bio-preservatives, such as bacteriocins, to extend the shelf life and improve the safety of meat products [89]. Fermentative microbes, such as *Lactobacillus* species, are used to ferment meat, producing organic acids and antimicrobial peptides that inhibit the growth of spoilage and pathogenic microorganisms [90]. Bio-preservatives, such as nisin and pediocin, are naturally occurring antimicrobial peptides produced by certain bacteria that can be added to meat products to control microbial growth [91]. Innovations in this area include the development of specialized starter cultures that are tailored to specific meat products, improving flavor, texture, and safety while reducing the need for chemical preservatives [92]. Research is also focused on the production of novel bacteriocins with broader antimicrobial spectra and enhanced stability under various processing conditions [93].

Irradiation and UV processing are technologies that use ionizing radiation and ultraviolet light, respectively, to inactivate pathogens and extend the shelf life of meat products [94]. Irradiation exposes meat to gamma rays, X-rays, or electron beams, which disrupt the DNA of microorganisms, effectively reducing the microbial load [95]. UV processing involves the use of UV–C light to penetrate the surface of meat and kill bacteria and viruses [96].

These technologies offer significant potential for pathogen control and shelf-life extension without the use of chemical additives or high temperatures. However, consumer perception and regulatory challenges remain obstacles to widespread adoption. Consumers often associate irradiation with negative connotations, such as "radiation" and "radioactivity," despite extensive evidence demonstrating its safety and efficacy [97,98]. Regulatory bodies in different countries have varying standards and approval processes for irradiation and UV treatments, further complicating their implementation in the global meat industry [99,100]. Ongoing research aims to improve effectiveness of these technologies while addressing consumer concerns through education and transparent communication about the benefits and safety of these methods.

Table 1. Comparison of green processing technologies: energy consumption, waste reduction, cost, and microbial inactivation

Technology	Energy consumption	Waste reduction	Cost	Microbial inactivation
HPP	Low	High	High	Very effective
PEF	Moderate	Moderate	Moderate	Effective
Cold plasma	Low	Moderate	High	Effective
Ultrasound	Moderate	Low	Moderate	Moderate

Integration of novel green technologies in meat processing

The integration of novel green technologies in meat processing involves combining multiple methods to maximize their individual benefits and achieve superior product quality, safety, and sustainability (Table 2). Combination approaches leverage the synergistic effects of different green technologies to enhance microbial inactivation, preserve sensory and nutritional qualities, and reduce environmental impact [101]. For example, combining HPP with cold plasma can provide a dual mechanism of microbial inactivation, where HPP targets the internal pathogens while cold plasma efficiently decontaminates the meat surface [102]. This combination not only extends the shelf life of meat products but also minimizes the need for chemical preservatives and reduces energy consumption by lowering the required pressure levels and treatment times [103].

Another effective combination approach is using PEF processing with ultrasound technology [104]. While PEF disrupts microbial cell membranes to ensure food safety, ultrasound aids in tenderizing meat and enhancing marinade absorption, thereby improving texture and flavor [105]. This combined approach can significantly reduce the processing time and energy consumption compared to conventional methods, such as prolonged marination and heat treatments. By integrating these technologies, meat processors can achieve a more efficient and sustainable production process, meeting both industry standards and consumer demands for high-quality, minimally processed products.

Environmental impact and sustainability

Green processing technologies offer a more sustainable alternative to traditional meat processing methods by significantly reducing their environmental impact [113]. Traditional meat processing methods, such as curing, smoking, and chemical preservation, often rely heavily on energy-intensive processes, high water usage, and the application of synthetic chemicals. These methods contribute to higher greenhouse gas emissions, increased water pollution from chemical runoff, and excessive energy consumption [114]. In contrast, green processing technologies, such as HPP, PEF, and cold plasma technology, are designed to minimize energy usage, reduce waste, and lower chemical inputs [11]. For example, PEF and ultrasound technologies require less energy compared to conventional thermal processing methods, as they operate at lower temperatures and reduce processing times [115]. Similarly, HPP and cold plasma do not produce harmful emissions or chemical residues, thereby reducing the environmental footprint of meat processing [102]. Overall, green technologies provide a cleaner, more efficient alternative that aligns with global sustainability goals and consumer demand for environmentally friendly products.

Recent LCAs of green processing technologies in the meat processing industry highlight their environmental advantages across several impact categories, including carbon footprint, water usage, and energy consumption [116]. Studies have shown that technologies such as HPP and PEF have a significantly lower carbon footprint compared to traditional heat treatments. For instance, an LCA study comparing HPP to conventional thermal pasteurization found that HPP resulted in a 30–40% reduction in greenhouse gas emissions due to lower energy consumption and the elimination of heat production [117]. Additionally, an assessment of cold plasma technology demonstrated its potential to reduce water usage by up to 50% compared to chemical-based decontamination methods, as it requires no water or chemical solvents [118]. These findings suggest that green processing technologies can substantially reduce the environmental impact of meat production throughout the entire product life cycle, from raw material processing to waste management.

Table 2. Case study comparison of green processing technologies: impacts on microbial reduction, shelf life extension, and quality attributes of meat and meat products

Processing method	Meat product	Microbial reduction	Shelf life extension	Impact on quality attributes	Specific microorganisms affected	Reference
HPP	Bratwurst sausages	Total microbial count reduced by up to 4.2 log CFU/g; LAB reduced from 2.4 to 1 log CFU/g	5–8 times longer than untreated	No alteration in color and texture of treated samples.	Significant reduction of *Pseudomonas* spp., *Enterobacteriaceae*, yeasts and molds, *Staphylococcus* spp., *Brochothrix thermosphacta* (below detection limits throughout storage period).	[106]
Cold plasma + modified atmosphere packaging	Meatballs	Initial microbial counts decreased by 1.02 to 1.19 log CFU/g with 6–9 min Ar-based treatment	Extended by 14 days	Slight increase in lipid oxidation values (Ar-6 min: 0.93 mg/kg; Ar-9 min: 0.92 mg/kg) compared to control (0.83 mg/kg); no significant change in TVB-N.	Reduction in relative abundance of unclassified-*Enterobacteriaceae* (19.04% to 12.54%) and Acinetobacter (30.88% to 2.25%) in the Ar-6 min group.	[107]
Cold plasma using argon, helium, nitrogen	Various meat surfaces	Decreased psychrotrophic and total bacteria by 2–3 log CFU/cm² (argon and helium, respectively)	—	No significant interaction with nitrogen for psychrotrophic bacteria; reduction in yeasts and molds by 1 log CFU/cm² after 10 min.	Decrease in psychrotrophic bacteria and total bacteria with argon and helium treatment; nitrogen treatment primarily affected yeasts and molds.	[108]
High-intensity ultrasound (HIU)	Semitendinosus beef muscle	Decreased counts of mesophilic, psychrophilic bacteria, *Staphylococcus* spp., and coliform bacteria	Extended during storage at 4°C	HIU decreased pH and color difference (ΔE from 5.99 to 1.43); drip loss decreased but was similar to control at the end of 9 days; no difference in water-holding capacity and shear force compared to controls.	Reduction in mesophilic, psychrophilic bacteria, *Staphylococcus* spp., and coliform bacteria.	[109]
Moderate intensity pulsed electric field (MIPEF)	Chicken breast meat	Total mesophilic aerobic bacteria (TMAB) count exceeded 2 days later in 4.67 and 7 kV/cm groups; Almost 2 log reduction in total coliform bacteria.	Extended by 2 days compared to control.	pH, CIE L*, b*, C* color values unaffected; ΔE values showed maximum change in the control group	*Pseudomonas aeruginosa* count remained unchanged; *E. coli* and *C. jejuni* showed resistance at 4.67 kV/cm and 7 kV/cm, respectively; *L. monocytogenes* growth promoted by 4.67 kV/cm.	[110]
Bio-preservation by LAB	Sliced fresh beef	Reduction in *Enterobacteriaceae*, *Staphylococcus*, coliforms, *L. monocytogenes* and *Salmonella* Typhimurium	—	—	*Salmonella* Typhimurium and *L. monocytogenes*	[111]
Gamma radiation	Fish meat	Aerobic Plate Count (APC) reduced by 100% at 5 KGy; pathogenic bacteria counts were reduced dose-dependently	Significantly extended, especially at higher doses	No significant effect on proximate composition; carbohydrates, proteins, and lipids were not significantly affected by low and medium doses of radiation	High prevalence of *Staphylococcus aureus* among untreated samples; pathogenic bacteria completely eradicated at 5 KGy.	[112]

Green processing technologies also offer innovative solutions for waste management and by-product utilization in the meat processing industry [119]. Traditional methods often generate significant amounts of organic waste, including meat scraps, fat trimmings, and bones, which are typically discarded or used for low-value applications [120]. In contrast, green technologies facilitate the conversion of these by-products into valuable resources [121]. For example, technologies such as fermentation and bio-preservation can utilize meat scraps and trimmings to produce bioenergy, bioplastics, or high-value protein hydrolysates for use in animal feed or nutritional supplements [122]. Moreover, processes such as cold plasma and ultrasound can enhance the recovery of collagen and gelatin from bone and connective tissue, contributing to the production of functional ingredients for the food and pharmaceutical industries [123]. By effectively managing waste and utilizing by-products, green technologies not only reduce the environmental impact of meat processing but also create additional revenue streams and promote a circular economy within the industry.

Economic feasibility and market potential

The economic feasibility of adopting green processing technologies at a commercial scale depends on several factors, including initial investment costs, operational expenses, and potential savings [124]. While the upfront costs for equipment such as HPP machines, PEF systems, and cold plasma generators can be substantial, these investments can lead to significant long-term savings [125]. Green technologies typically consume less energy and reduce water and chemical usage compared to traditional processing methods, leading to lower operational costs over time [126]. For instance, HPP systems, despite their high initial cost, can lower energy costs due to reduced processing times and the elimination of the need for high-temperature treatments [127]. Furthermore, the reduction in spoilage and waste, along with extended shelf life of products, can decrease overall production costs and increase profitability [128]. Additionally, government incentives and subsidies aimed at promoting sustainable practices can help offset the initial costs of adopting these green technologies. Companies that invest in these technologies may also gain a competitive advantage by differentiating their products in the marketplace as sustainable and environmentally friendly, potentially capturing a larger share of the growing market for green and clean-label products.

Market trends indicate a growing consumer demand for sustainably processed meat products, driven by increasing awareness of environmental issues and health concerns associated with traditional meat processing methods [44]. Consumers are becoming more conscious of the environmental impact of their food choices and are willing to pay a premium for products that are marketed as green, natural, or free from synthetic additives [129]. Surveys and market analyses show that there is a strong consumer preference for meat products processed with novel green technologies that retain natural flavors and nutrients without compromising food safety [130]. However, consumer acceptance of these products is influenced by several factors, including education about the benefits of green technologies, transparency in labeling, and trust in the safety and quality of the final products [34]. Effective communication and marketing strategies are essential to educate consumers about the advantages of green processing technologies and dispel any misconceptions regarding the safety and efficacy of these methods [131]. Additionally, as the market for green-processed meat products continues to expand, retailers and food service providers are increasingly incorporating these items into their offerings, further driving consumer acceptance and market penetration [132]. With a favorable market outlook and growing consumer demand, the adoption of green processing technologies presents a promising opportunity for meat processors to align with sustainability goals and cater to evolving consumer preferences.

Regulatory landscape and challenges

The regulatory landscape for green processing technologies in meat processing is evolving as governments and international organizations seek to address food safety, environmental sustainability, and public health concerns [133]. Currently, regulations on green technologies in meat processing vary significantly across regions, depending on the technology and its application. For example, in the United States, the Food and Drug Administration (FDA) and the United States Department of Agriculture (USDA) regulate technologies such as HPP and PEF processing, requiring comprehensive safety assessments and validation studies before these methods can be used commercially [134]. In the European Union, the European Food Safety Authority (EFSA) plays a similar role, establishing guidelines and safety standards for novel processing technologies, including cold plasma and ultrasound, to ensure they meet stringent safety and quality requirements [135]. Additionally, regulations around labeling and marketing of green-processed products are in place to ensure transparency and protect consumer interests [136]. While these regulations aim to safeguard public health and promote food safety, they can also be restrictive, requiring substantial documentation and scientific evidence to demonstrate that new technologies are safe and effective.

The adoption of green processing technologies in the meat industry faces several regulatory challenges, including the lengthy and complex approval processes, the need for extensive scientific validation, and the lack of harmonized international standards [137]. For many emerging technologies, such as cold plasma and UV processing, the regulatory framework is still developing, creating uncertainty for companies looking to innovate [135]. This uncertainty can deter investment and slow the commercialization of these technologies. Moreover, the rigorous safety assessments and validation studies required for regulatory approval can be costly and time-consuming, particularly for small and medium-sized enterprises (SMEs) [138]. Additionally, the lack of harmonization in regulations across different regions can pose challenges for global companies, as they must navigate multiple regulatory environments and adapt their technologies to meet diverse safety standards and requirements [139].

Despite these challenges, there are significant opportunities for advancing green processing technologies within the regulatory framework. Increased collaboration between industry stakeholders, regulatory bodies, and scientific communities can help develop more streamlined and flexible regulatory pathways. For example, establishing clear guidelines and protocols for validating the safety and efficacy of new technologies could accelerate their approval and adoption. Furthermore, as consumer demand for sustainable and minimally processed foods grows, there is a strong incentive for regulatory bodies to support innovations that enhance food safety and quality while reducing environmental impact. Developing a more supportive regulatory environment could encourage innovation, promote the adoption of green technologies, and ultimately lead to more sustainable and resilient food systems.

Future directions and research needs

The future of green processing technologies in the meat industry hinges on continued innovation and research. Key areas for future research include enhancing the efficiency and scalability of existing technologies and developing novel methods with broader applications. For instance, research could focus on improving the energy efficiency and cost-effectiveness of HPP and PEF systems, making them more accessible to smaller processors. Additionally, exploring the integration of green technologies with emerging smart processing systems, such as Internet of Things (IoT) and artificial intelligence (AI) for real-time monitoring and optimization, holds promise for advancing the industry. Innovations in materials and processes, such as biodegradable packaging and sustainable waste management solutions, are also crucial. By investing in these research areas, the meat processing industry can advance towards more sustainable practices, improve product quality, and meet the evolving demands of both regulators and consumers.

Encouraging the industry-wide adoption of green processing technologies involves addressing several challenges and implementing strategic initiatives. One key strategy is to provide financial incentives and support to companies that invest in green technologies, such as subsidies, tax breaks, or grants. This can help offset the high initial costs and facilitate a smoother transition. Additionally, fostering partnerships between technology developers, industry stakeholders, and government agencies can promote the sharing of knowledge, resources, and best practices. Industry associations and consortia can play a crucial role in setting standards, providing training, and demonstrating the benefits of green technologies through pilot projects and case studies. Engaging in collaborative efforts and creating a supportive ecosystem can accelerate the adoption of green technologies across the meat processing sector and drive widespread industry transformation.

Educating consumers about the benefits of green processing technologies is essential for driving market demand and acceptance. Initiatives to increase consumer awareness can include targeted marketing campaigns that highlight the environmental and health benefits of green-processed meat products. Transparency in labeling, including clear information about the use of green technologies and their advantages, can help build consumer trust and confidence. Public education campaigns, in partnership with industry organizations, environmental groups, and academic institutions, can further enhance understanding and support for sustainable practices. Additionally, incorporating educational content into food safety and nutrition programs can raise awareness from an early age. By fostering a well-informed consumer base, the meat industry can encourage the adoption of green processing technologies and contribute to a more sustainable food system.

Conclusion

Green processing technologies offer transformative benefits for the meat industry, enhancing food safety, quality, and sustainability. These methods, such as high-pressure processing and cold plasma, reduce energy consumption, minimize chemical use, and improve waste management. They represent a significant step towards addressing environmental and health challenges associated with traditional meat processing. To maximize their potential, it is essential to advance research, develop supportive policies, and encourage industry adoption. Collaborative efforts, innovative solutions, and consumer education will drive the widespread implementation of these technologies, leading to a more sustainable and efficient meat production system.

REFERENCES

1. Qu, B., Xiao, Z., Upadhyay, A., Luo, Y. (2024). Perspectives on sustainable food production system: Characteristics and green technologies. *Journal of Agriculture and Food Research*, 15, Article 100988. https://doi.org/10.1016/j.jafr.2024.100988
2. Corigliano, O., Algieri, A. (2024). A comprehensive investigation on energy consumptions, impacts, and challenges of the food industry. *Energy Conversion and Management: X*, 23, Article 100661. https://doi.org/10.1016/j.ecmx.2024.100661
3. McDonagh, M., O'Donovan, S., Moran, A., Ryan, L. (2024). An exploration of food sustainability practices in the food industry across Europe. *Sustainability*, 16(16), Article 7119. https://doi.org/10.3390/su16167119

4. Pathiraje, D., Carlin, J., Der, T., Wanasundara, J.P., Shand, P.J. (2023). Generating multi-functional pulse ingredients for processed meat products — scientific evaluation of infrared-treated lentils. *Foods*, 12(8), Article 1722. https://doi.org/10.3390/foods12081722
5. Jia, Z., Zhang, B., Sharma, A., Kim, N.S., Purohit, S.M., Green, M.M. et al. (2023). Revelation of the sciences of traditional foods. *Food Control*, 145, Article 109392. https://doi.org/10.1016/j.foodcont.2022.109392
6. Novais, C., Molina, A. K., Abreu, R. M. V., Santo-Buelga, C., Ferreira, I. C. F. R., Pereira, C. et al. (2022). Natural food colorants and preservatives: A review, a demand, and a challenge. *Journal of Agricultural and Food Chemistry*, 70(9), 2789–2805. https://doi.org/10.1021/acs.jafc.1c07533
7. Gómez, I., Janardhanan, R., Ibañez, F. C., Beriain, M. J. (2020). The effects of processing and preservation technologies on meat quality: Sensory and nutritional aspects. *Foods*, 9(10), Article 1416. https://doi.org/10.3390/foods9101416
8. Pinton, M. B., dos Santos, B. A., Lorenzo, J. M., Cichoski, A. J., Boeira, C. P., Campagnol, P. C. B. (2021). Green technologies as a strategy to reduce NaCl and phosphate in meat products: An overview. *Current Opinion in Food Science*, 40, 1–5. https://doi.org/10.1016/j.cofs.2020.03.011
9. Pinto, V. R. A., de Abreu Campos, R. F., Rocha, F., Emmendoerfer, M. L., Vidigal, M. C. T. R., da Rocha, S. J. S. S. et al. (2021). Perceived healthiness of foods: A systematic review of qualitative studies. *Future Foods*, 4, Article 100056. https://doi.org/10.1016/j.fufo.2021.100056
10. Soro, A. B., Noore, S., Hannon, S., Whyte, P., Bolton, D. J., O'Donnell, C. et al. (2021). Current sustainable solutions for extending the shelf life of meat and marine products in the packaging process. *Food Packaging and Shelf Life*, 29, Article 100722. https://doi.org/10.1016/j.fpsl.2021.100722
11. Picart-Palmade, L., Cunault, C., Chevalier-Lucia, D., Belleville, M.-P., Marchesseau, S. (2019). Potentialities and limits of some non-thermal technologies to improve sustainability of food processing. *Frontiers in Nutrition*, 5, Article 130. https://doi.org/10.3389/fnut.2018.00130
12. Nabi, B. G., Mukhtar, K., Arshad, R. N., Radicetti, E., Tedeschi, P., Shahbaz, M. U. et al. (2021). High-pressure processing for sustainable food supply. *Sustainability*, 13(24), Article 13908. https://doi.org/10.3390/su132413908
13. Ucar, Y., Ceylan, Z., Durmus, M., Tomar, O., Cetinkaya, T. (2021). Application of cold plasma technology in the food industry and its combination with other emerging technologies. *Trends in Food Science and Technology*, 114, 355–371. https://doi.org/10.1016/j.tifs.2021.06.004
14. Alarcon-Rojo, A. D., Carrillo-Lopez, L. M., Reyes-Villagrana, R., Huerta-Jiménez, M., Garcia-Galicia, I. A. (2019). Ultrasound and meat quality: A review. *Ultrasonics Sonochemistry*, 55, 369–382. https://doi.org/10.1016/j.ultsonch.2018.09.016
15. Arshad, R. N., Abdul-Malek, Z., Roobab, U., Munir, M. A., Naderipour, A., Qureshi, M. I. et al. (2021). Pulsed electric field: A potential alternative towards a sustainable food processing. *Trends in Food Science and Technology*, 111, 43–54. https://doi.org/10.1016/j.tifs.2021.02.041
16. Augustin, M. A., Hartley, C. J., Maloney, G., Tyndall, S. (2024). Innovation in precision fermentation for food ingredients. *Critical Reviews in Food Science and Nutrition*, 64(18), 6218–6238. https://doi.org/10.1080/10408398.2023.2166014
17. Khan, N., Ray, R. L., Kassem, H. S., Hussain, S., Zhang, S., Khayyam, M. et al. (2021). Potential role of technology innovation in transformation of sustainable food systems: A review. *Agriculture*, 11(10), Article 984. https://doi.org/10.3390/agriculture11100984
18. Jiang, G., Ameer, K., Kim, H., Lee, E.-J., Ramachandraiah, K., Hong, G.-P. (2020). Strategies for sustainable substitution of livestock meat. *Foods*, 9(9), Article 1227. https://doi.org/10.3390/foods9091227
19. Fraqueza, M. J., Laranjo, M., Alves, S., Fernandes, M. H., Agulheiro-Santos, A. C., Fernandes, M. J. et al. (2020). Dry-cured meat products according to the smoking regime: Process optimization to control polycyclic aromatic hydrocarbons. *Foods*, 9(1), Article 91. https://doi.org/10.3390/foods9010091
20. Halagarda, M., Wójciak, K. M. (2022). Health and safety aspects of traditional European meat products. A review. *Meat Science*, 184, Article 108623. https://doi.org/10.1016/j.meatsci.2021.108623
21. Cardoso, P. da S., Fagundes, J. M., Couto, D. S., Pires, E. de M., Guimarães, C. E. D., Ribeiro, C. D. F. et al. (2020). From curing to smoking: Processes and techniques for the production of pastrami. *Brazilian Journal of Development*, 6(8), 61511–61520. https://doi.org/10.34117/bjdv6n8-538
22. Hassoun, A., Guðjónsdóttir, M., Prieto, M. A., Garcia-Oliveira, P., Simal-Gandara, J., Marini, F. et al. (2020). Application of novel techniques for monitoring quality changes in meat and fish products during traditional processing processes: Reconciling novelty and tradition. *Processes*, 8(8), Article 988. https://doi.org/10.3390/pr8080988
23. Molina, J. R. G., Frías-Celayeta, J. M., Bolton, D. J., Botinestean, C. (2024). A comprehensive review of cured meat products in the irish market: Opportunities for reformulation and processing. *Foods*, 13(5), Article 746. https://doi.org/10.3390/foods13050746
24. Munir, M. T., Mtimet, N., Guillier, L., Meurens, F., Fravalo, P., Federighi, M. et al. (2023). Physical treatments to control *Clostridium botulinum* hazards in food. *Foods*, 12(8), Article 1580. https://doi.org/10.3390/foods12081580
25. Deveci, G., Tek, N.A. (2024). N-Nitrosamines: A potential hazard in processed meat products. *Journal of the Science of Food and Agriculture*, 104(5), 2551–2560. https://doi.org/10.1002/jsfa.13102
26. Xiao-Hui, G., Jing, W., Ye-Ling, Z., Ying, Z., Qiu-Jin, Z., Ling-Gao, L. et al. (2023). Mediated curing strategy: An overview of salt reduction for dry-cured meat products. *Food Reviews International*, 39(7), 4565–4580. https://doi.org/10.1080/87559129.2022.2029478
27. Das, A.K., Bhattacharya, D., Das, A., Nath, S., Bandyopadhyay, S., Nanda, P. K. et al. (2023). Current innovative approaches in reducing polycyclic aromatic hydrocarbons (PAHs) in processed meat and meat products. *Chemical and Biological Technologies in Agriculture*, 10(1), Article 109. https://doi.org/10.1186/s40538-023-00483-8
28. Nizio, E., Czwartkowski, K., Niedbała, G. (2023). Impact of smoking technology on the quality of food products: Absorption of polycyclic aromatic hydrocarbons (PAHs) by food products during smoking. *Sustainability*, 15(24), Article 16890. https://doi.org/10.3390/su152416890
29. Adeyeye, S. A. O., Ashaolu, T. J. (2022). Polycyclic aromatic hydrocarbons formation and mitigation in meat and meat products. *Polycyclic Aromatic Compounds*, 42(6), 3401–3411. https://doi.org/10.1080/10406638.2020.1866039
30. Bulanda, S., Janoszka, B. (2022). Consumption of thermally processed meat containing carcinogenic compounds (polycyclic aromatic hydrocarbons and heterocyclic aromatic amines) versus a risk of some cancers in humans and the possibility of reducing their formation by natural food additives — a literature review. *International Journal of Environmental Research and Public Health*, 19(8), Article 4781. https://doi.org/10.3390/ijerph19084781
31. Bamwesigye, D., Kupec, P., Chekuimo, G., Pavlis, J., Asamoah, O., Darkwah, S. A. et al. (2020). Charcoal and wood biomass utilization in Uganda: The socioeconomic and environmental dynamics and implications. *Sustainability*, 12(20), Article 8337. https://doi.org/10.3390/su12208337

32. Bensid, A., El Abed, N., Houicher, A., Regenstein, J. M., Özogul, F. (2022). Antioxidant and antimicrobial preservatives: Properties, mechanism of action and applications in food–a review. *Critical Reviews in Food Science and Nutrition*, 62(11), 2985–3001. https://doi.org/10.1080/10408398.2020.1862046
33. Sharma, H., Rajput, R. (2023). The science of food preservation: A comprehensive review of synthetic preservatives. *Journal of Current Research in Food Science*, 4(2), 25–29.
34. Font-i-Furnols, M. (2023). Meat consumption, sustainability and alternatives: An overview of motives and barriers. *Foods*, 12(11), Article 2144. https://doi.org/10.3390/foods12112144
35. Rodríguez Escobar, M. I., Cadena, E., Nhu, T. T., Cooreman-Algoed, M., De Smet, S., Dewulf, J. (2021). Analysis of the cultured meat production system in function of its environmental footprint: Current status, gaps and recommendations. *Foods*, 10(12), Article 2941. https://doi.org/10.3390/foods10122941
36. Teshome, E., Forsido, S. F., Rupasinghe, H. P. V., Olika Keyata, E. (2022). Potentials of natural preservatives to enhance food safety and shelf life: A review. *The Scientific World Journal*, 2022(1), Article 9901018. https://doi.org/10.1155/2022/9901018
37. Wojtasik-Kalinowska, I., Szpicer, A., Binkowska, W., Hanula, M., Marcinkowska-Lesiak, M., Poltorak, A. (2023). Effect of processing on volatile organic compounds formation of meat. *Applied Sciences,* 13(2), Article 705. https://doi.org/10.3390/app13020705
38. Dutta, K., Shityakov, S., Zhu, W., Khalifa, I. (2022). High-risk meat and fish cooking methods of polycyclic aromatic hydrocarbons formation and its avoidance strategies. *Food Control*, 142, Article 109253. https://doi.org/10.1016/j.foodcont.2022.109253
39. Giampieri, A., Ling-Chin, J., Ma, Z., Smallbone, A., Roskilly, A. (2020). A review of the current automotive manufacturing practice from an energy perspective. *Applied Energy*, 261, Article 114074. https://doi.org/10.1016/j.apenergy.2019.114074
40. Dai, B., Cao, Y., Zhou, X., Liu, S., Fu, R., Li, C. et al. (2024). Exergy, carbon footprint and cost lifecycle evaluation of cascade mechanical subcooling CO2 commercial refrigeration system in China. *Journal of Cleaner Production*, 434, Article 140186. https://doi.org/10.1016/j.jclepro.2023.140186
41. Chen, Y., Zhang, X., Ji, J., Zhang, C. (2024). Cold chain transportation energy conservation and emission reduction based on phase change materials under dual-carbon background: A review. *Journal of Energy Storage*, 86, Article 111258. https://doi.org/10.1016/j.est.2024.111258
42. Seibt, A. C. M. D., Nerhing, P., Pinton, M. B., Santos, S. P., Leães, Y. S. V., De Oliveira, F. D. C. et al. (2024). Green technologies applied to low-NaCl fresh sausages production: Impact on oxidative stability, color formation, microbiological properties, volatile compounds, and sensory profile. *Meat Science*, 209, Article 109418. https://doi.org/10.1016/j.meatsci.2023.109418
43. Boukouvalas, C., Kekes, T., Oikonomopoulou, V., Krokida, M. (2024). Life cycle assessment of energy production from solid waste valorization and wastewater purification: A case study of meat processing industry. *Energies*, 17(2), Article 487. https://doi.org/10.3390/en17020487
44. Inguglia, E. S., Song, Z., Kerry, J. P., O'Sullivan, M. G., Hamill, R. M. (2023). Addressing clean label trends in commercial meat processing: Strategies, challenges and insights from consumer perspectives. *Foods*, 12(10), Article 2062. https://doi.org/10.3390/foods12102062
45. Kumar, P., Abubakar, A. A., Verma, A. K., Umaraw, P., Adewale Ahmed, M., Mehta, N. et al. (2023). New insights in improving sustainability in meat production: Opportunities and challenges. *Critical Reviews in Food Science and Nutrition*, 63(33), 11830–11858. https://doi.org/10.1080/10408398.2022.2096562
46. Aydin, M., Degirmenci, T. (2024). The impact of clean energy consumption, green innovation, and technological diffusion on environmental sustainability: New evidence from load capacity curve hypothesis for 10 European Union countries. *Sustainable Development,* 32(3), 2358–2370. https://doi.org/10.1002/sd.2794
47. Li, Z., Yang, Q., Du, H., Wu, W. (2023). Advances of pulsed electric field for foodborne pathogen sterilization. *Food Reviews International*, 39(7), 3603–3619. https://doi.org/10.1080/87559129.2021.2012798
48. Lopes, S. J. S., S. Sant'Ana, A., Freire, L. (2023). Non-thermal emerging processing technologies: mitigation of microorganisms and mycotoxins, sensory and nutritional properties maintenance in clean label fruit juices. *Food Research International*, 168, Article 112727. https://doi.org/10.1016/j.foodres.2023.112727
49. Ashrafudoulla, Md., Ulrich, M. S. I., Toushik, S. H., Nahar, S., Roy, P. K., Mizan, F. R. et al. (2023). Challenges and opportunities of non-conventional technologies concerning food safety. *World's Poultry Science Journal*, 79(1), 3–26. https://doi.org/10.1080/00439339.2023.2163044
50. Liu, X., Xie, Y., Sheng, H. (2023). Green waste characteristics and sustainable recycling options. *Resources, Environment and Sustainability*, 11, Article 100098. https://doi.org/10.1016/j.resenv.2022.100098
51. Hamed, I., Jakobsen, A. N., Lerfall, J. (2022). Sustainable edible packaging systems based on active compounds from food processing byproducts: A review. *Comprehensive Reviews in Food Science and Food Safety*, 21(1), 198–226. https://doi.org/10.1111/1541-4337.12870
52. Gavahian, M., Mathad, G. N., Pandiselvam, R., Lin, J., Sun, D.-W. (2021). Emerging technologies to obtain pectin from food processing by-products: A strategy for enhancing resource efficiency. *Trends in Food Science and Technology*, 115, 42–54. https://doi.org/10.1016/j.tifs.2021.06.018
53. Castro-Muñoz, R., García-Depraect, O., León-Becerril, E., Cassano, A., Conidi, C., Fíla, V. (2021). Recovery of protein-based compounds from meat by-products by membrane-assisted separations: A review. *Journal of Chemical Technology and Biotechnology*, 96(11), 3025–3042. https://doi.org/10.1002/jctb.6824
54. Barone, A. S., Matheus, J. R. V., de Souza, T. S. P., Moreira, R. F. A., Fai, A. E. C. (2021). Green-based active packaging: Opportunities beyond COVID-19, food applications, and perspectives in circular economy-A brief review. *Comprehensive Reviews in Food Science and Food Safety*, 20(5), 4881–4905. https://doi.org/10.1111/1541-4337.12812
55. Carpentieri, S., Soltanipour, F., Ferrari, G., Pataro, G., Donsì, F. (2021). Emerging green techniques for the extraction of antioxidants from agri-food by-products as promising ingredients for the food industry. *Antioxidants*, 10(9), Article 1417. https://doi.org/10.3390/antiox10091417
56. Wu, L., Zhang, C., Long, Y., Chen, Q., Zhang, W., Liu, G. (2022). Food additives: From functions to analytical methods. *Critical Reviews in Food Science and Nutrition*, 62(30), 8497–8517. https://doi.org/10.1080/10408398.2021.1929823
57. Ahmed, S. F., Mofijur, M., Rafa, N., Chowdhury, A. T., Chowdhury, S., Nahrin, M. et al. (2022). Green approaches in synthesising nanomaterials for environmental nanobioremediation: Technological advancements, applications, benefits and challenges. *Environmental Research*, 204, Article 111967. https://doi.org/10.1016/j.envres.2021.111967
58. Albert, T., Braun, P. G., Saffaf, J., Wiacek, C. (2021). Physical methods for the decontamination of meat surfaces. *Current Clinical Microbiology Reports*, 8(2), 9–20. https://doi.org/10.1007/s40588-021-00156-w
59. Bradu, P., Biswas, A., Nair, C., Sreevalsakumar, S., Patil, M., Kannampuzha, S. et al. (2023). Recent advances in green technology and Industrial Revolution 4.0 for a sustainable future. *Environmental Science and Pollution Research*, 30(60), 124488–124519. https://doi.org/10.1007/s11356-022-20024-4

60. Galanakis, C. M. (2024). The future of food. *Foods*, 13(4), Article 506. https://doi.org/10.3390/foods13040506
61. Keyata, E., Bikila, A. (2024). Effect of high-pressure processing on nutritional composition, microbial safety, shelf life and sensory properties of perishable food products: A review. *Journal of Agriculture, Food and Natural Resources*, 2(1), 69–78. https://doi.org/10.20372/afnr.v2i1.659
62. Sehrawat, R., Kaur, B. P., Nema, P. K., Tewari, S., Kumar, L. (2021). Microbial inactivation by high pressure processing: Principle, mechanism and factors responsible. *Food Science and Biotechnology*, 30(1), 19–35. https://doi.org/10.1007/s10068-020-00831-6
63. Gokul Nath, K., Pandiselvam, R., Sunil, C. K. (2023). High-pressure processing: Effect on textural properties of food-A review. J*ournal of Food Engineering,* 351, Article 111521. https://doi.org/10.1016/j.jfoodeng.2023.111521
64. Inanoglu, S., Barbosa-Cánovas, G. V., Sablani, S. S., Zhu, M. J., Keener, L., Tang, J. (2022). High-pressure pasteurization of low-acid chilled ready-to-eat food. *Comprehensive Reviews in Food Science and Food Safety*, 21(6), 4939–4970. https://doi.org/10.1111/1541-4337.13058
65. Silva, F. V. M., Evelyn, E. (2023). Pasteurization of food and beverages by high pressure processing (HPP) at room temperature: Inactivation of *Staphylococcus aureus*, *Escherichia coli*, *Listeria monocytogenes*, Salmonella, and other microbial pathogens. *Applied Sciences*, 13(2), Article 1193. https://doi.org/10.3390/app13021193
66. Bernardo, Y. A. de A., do Rosario, D. K. A., Conte-Junior, C. A. (2023). Principles, application, and gaps of high-intensity ultrasound and high-pressure processing to improve meat texture. *Foods*, 12(3), Article 476. https://doi.org/10.3390/foods12030476
67. Chuang, S., Sheen, S. (2022). High pressure processing of raw meat with essential oils-microbial survival, meat quality, and models: A review. *Food Control*, 132, Article 108529. https://doi.org/10.1016/j.foodcont.2021.108529
68. de Souza, V. R., Popović, V., Bissonnette, S., Ros, I., Mats, L., Duizer, L. et al. (2020). Quality changes in cold pressed juices after processing by high hydrostatic pressure, ultraviolet-c light and thermal treatment at commercial regimes. *Innovative Food Science and Emerging Technologies*, 64, Article 102398. https://doi.org/10.1016/j.ifset.2020.102398
69. Varilla, C., Marcone, M., Annor, G. A. (2020). Potential of cold plasma technology in ensuring the safety of foods and agricultural produce: A review. *Foods*, 9(10), Article 1435. https://doi.org/10.3390/foods9101435
70. 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
71. Abdel-Naeem, H. H. S., Ebaid, E. M. S. M., Khalel, K. H. M., Imre, K., Morar, A., Herman, V. et al. (2022). Decontamination of chicken meat using dielectric barrier discharge cold plasma technology: The effect on microbial quality, physicochemical properties, topographical structure, and sensory attributes. *LWT*, 165, Article 113739. https://doi.org/10.1016/j.lwt.2022.113739
72. Yepez, X., Illera, A. E., Baykara, H., Keener, K. (2022). Recent advances and potential applications of atmospheric pressure cold plasma technology for sustainable food processing. *Foods*, 11(13), Article 1833. https://doi.org/10.3390/foods11131833
73. Pankaj, S. K., Wan, Z., Keener, K. M. (2018). Effects of cold plasma on food quality: A review. *Foods*, 7(1), Article 4. https://doi.org/10.3390/foods7010004
74. Chizoba Ekezie, F.-G., Sun, D.-W., Cheng, J.-H. (2017). A review on recent advances in cold plasma technology for the food industry: Current applications and future trends. *Trends in Food Science and Technology*, 69, 46–58. https://doi.org/10.1016/j.tifs.2017.08.007
75. Gallo, M., Ferrara, L., Naviglio, D. (2018). Application of ultrasound in food science and technology: A perspective. *Foods*, 7(10), Article 164. https://doi.org/10.3390/foods7100164
76. Peña-Gonzalez, E., Alarcon-Rojo, A. D., Garcia-Galicia, I., Carrillo-Lopez, L., Huerta-Jimenez, M. (2019). Ultrasound as a potential process to tenderize beef: Sensory and technological parameters. *Ultrasonics Sonochemistry*, 53, 134–141. https://doi.org/10.1016/j.ultsonch.2018.12.045
77. Gonzalez-Gonzalez, L., Alarcon-Rojo, A. D., Carrillo-Lopez, L. M., Garcia-Galicia, I. A., Huerta-Jimenez, M., Paniwnyk, L. (2020). Does ultrasound equally improve the quality of beef? An insight into longissimus lumborum, infraspinatus and cleidooccipitalis. *Meat Science*, 160, Article 107963. https://doi.org/10.1016/j.meatsci.2019.107963
78. Singla, M., Sit, N. (2021). Application of ultrasound in combination with other technologies in food processing: A review. *Ultrasonics Sonochemistry,* 73, Article 105506. https://doi.org/10.1016/j.ultsonch.2021.105506
79. Al-Hilphy, A. R., Al-Temimi, A. B., Al Rubaiy, H. H. M., Anand, U., Delgado-Pando, G., Lakhssassi, N. (2020). Ultrasound applications in poultry meat processing: A systematic review. *Journal of Food Science*, 85(5), 1386–1396. https://doi.org/10.1111/1750-3841.15135
80. Bariya, A. R., Rathod, N. B., Patel, A. S., Nayak, J. K. B., Ranveer, R. C., Hashem, A. et al. (2023). Recent developments in ultrasound approach for preservation of animal origin foods. *Ultrasonics Sonochemistry*, 101, Article 106676. https://doi.org/10.1016/j.ultsonch.2023.106676
81. Bhat, Z. F., Morton, J. D., Mason, S. L., Bekhit, A. E. A. (2018). Applied and emerging methods for meat tenderization: A comparative perspective. *Comprehensive Reviews in Food Science and Food Safety*, 17(4), 841–859. https://doi.org/10.1111/1541-4337.12356
82. Vanga, S. K., Wang, J., Jayaram, S., Raghavan, V. (2021). Effects of pulsed electric fields and ultrasound processing on proteins and enzymes: A review. *Processes*, 9(4), Article 722. https://doi.org/10.3390/pr9040722
83. Rebezov, M., Chughtai, M.F.J., Mehmood, T., Khaliq, A., Tanweer, S., Semenova, A. et al. (2021). Novel techniques for microbiological safety in meat and fish industries. *Applied Sciences*, 12(1), Article 319. https://doi.org/10.3390/app12010319
84. Gómez, B., Munekata, P. E. S., Gavahian, M., Barba, F. J., Martí-Quijal, F. J., Bolumar, T. et al. (2019). Application of pulsed electric fields in meat and fish processing industries: An overview. *Food Research International*, 123, 95–105. https://doi.org/10.1016/j.foodres.2019.04.047
85. Kantono, K., Hamid, N., Chadha, D., Ma, Q., Oey, I., Farouk, M. M. (2021). Pulsed electric field (PEF) processing of chilled and frozen-thawed lamb meat cuts: Relationships between sensory characteristics and chemical composition of meat. *Foods*, 10(5), Article 1148. https://doi.org/10.3390/foods10051148
86. Naliyadhara, N., Kumar, A., Girisa, S., Daimary, U. D., Hegde, M., Kunnumakkara, A. B. (2022). Pulsed electric field (PEF): Avant-garde extraction escalation technology in food industry. *Trends in Food Science and Technology*, 122, 238–255. https://doi.org/10.1016/j.tifs.2022.02.019
87. Zhang, H., Tikekar, R. V., Ding, Q., Gilbert, A. R., Wimsatt, S. T. (2020). Inactivation of foodborne pathogens by the synergistic combinations of food processing technologies and food-grade compounds. *Comprehensive Reviews in Food Science and Food Safety*, 19(4), 2110–2138. https://doi.org/10.1111/1541-4337.12582
88. Aaliya, B., Valiyapeediyekkal Sunooj, K., Navaf, M., Parambil Akhila, P., Sudheesh, C., Ahmad Mir, S. et al. (2021). Recent trends in bacterial decontamination of food products by hurdle technology: A synergistic approach using thermal and non-thermal processing techniques. *Food Research International*, 147, Article 110514. https://doi.org/10.1016/j.foodres.2021.110514

89. Rathod, N. B., Phadke, G. G., Tabanelli, G., Mane, A., Ranveer, R. C., Pagarkar, A. et al. (2021). Recent advances in bio-preservatives impacts of lactic acid bacteria and their metabolites on aquatic food products. *Food Bioscience*, 44, Article 101440. https://doi.org/10.1016/j.fbio.2021.101440
90. Kaveh, S., Hashemi, S. M. B., Abedi, E., Amiri, M. J., Conte, F. L. (2023). Bio-preservation of meat and fermented meat products by lactic acid bacteria strains and their antibacterial metabolites. *Sustainability*, 15(13), Article 10154. https://doi.org/10.3390/su151310154
91. Amiri, S., Motalebi Moghanjougi, Z., Rezazadeh Bari, M., Mousavi Khaneghah, A. (2021). Natural protective agents and their applications as bio-preservatives in the food industry: An overview of current and future applications. *Italian Journal of Food Science*, 33(SP1), 55–68. https://doi.org/10.15586/ijfs.v33iSP1.2045
92. Ursachi, C.Ș., Perța-Crișan, S., Munteanu, F.-D. (2020). Strategies to improve meat products' quality. *Foods*, 9(12), Article 1883. https://doi.org/10.3390/foods9121883
93. Zimina, M., Babich, O., Prosekov, A., Sukhikh, S., Ivanova, S., Shevchenko, M. et al. (2020). Overview of global trends in classification, methods of preparation and application of bacteriocins. *Antibiotics*, 9(9), Article 553. https://doi.org/10.3390/antibiotics9090553
94. Wang, J., Chen, J., Sun, Y., He, J., Zhou, C., Xia, Q. et al. (2023). Ultraviolet-radiation technology for preservation of meat and meat products: Recent advances and future trends. *Food Control*, 148, Article 109684. https://doi.org/10.1016/j.foodcont.2023.109684
95. Indiarto, R., Irawan, A. N., Subroto, E. (2023). Meat irradiation: A comprehensive review of its impact on food quality and safety. *Foods*, 12(9), Article 1845. https://doi.org/10.3390/foods12091845
96. Singh, H., Bhardwaj, S. K., Khatri, M., Kim, K.-H., Bhardwaj, N. (2021). UVC radiation for food safety: An emerging technology for the microbial disinfection of food products. *Chemical Engineering Journal*, 417, Article 128084. https://doi.org/10.1016/j.cej.2020.128084
97. Balatsas-Lekkas, A., Arvola, A., Kotilainen, H., Meneses, N., Pennanen, K. (2020). Effect of labelling fresh cultivated blueberry products with information about irradiation technologies and related benefits on Finnish, German, and Spanish consumers' product acceptance. *Food Control*, 118, Article 107387. https://doi.org/10.1016/j.foodcont.2020.107387
98. D'Souza, C., Apaolaza, V., Hartmann, P., Brouwer, A. R., Nguyen, N. (2021). Consumer acceptance of irradiated food and information disclosure–A retail imperative. *Journal of Retailing and Consumer Services*, 63, Article 102699. https://doi.org/10.1016/j.jretconser.2021.102699
99. Rowan, N. J. (2023). Current decontamination challenges and potentially complementary solutions to safeguard the vulnerable seafood industry from recalcitrant human norovirus in live shellfish: Quo Vadis? *Science of the Total Environment*, 874, Article 162380. https://doi.org/10.1016/j.scitotenv.2023.162380
100. Baggio, A., Marino, M., Innocente, N., Celotto, M., Maifreni, M. (2020). Antimicrobial effect of oxidative technologies in food processing: An overview. *European Food Research and Technology*, 246(4), 669–692. https://doi.org/10.1007/s00217-020-03447-6
101. Franco-Vega, A., Reyes-Jurado, F., González-Albarrán, D., Ramírez-Corona, N., Palou, E., López-Malo, A. (2021). Developments and advances of high intensity pulsed light and its combination with other treatments for microbial inactivation in food products. *Food Engineering Reviews*, 13, 741–768. https://doi.org/10.1007/s12393-021-09280-1
102. Roobab, U., Chacha, J. S., Abida, A., Rashid, S., Muhammad Madni, G., Lorenzo, J. M. et al. (2022). Emerging trends for nonthermal decontamination of raw and processed meat: Ozonation, high-hydrostatic pressure and cold plasma. *Foods*, 11(15), Article 2173. https://doi.org/10.3390/foods11152173
103. Nema, P. K., Sehrawat, R., Ravichandran, C., Kaur, B. P., Kumar, A., Tarafdar, A. (2022). Inactivating food microbes by high-pressure processing and combined nonthermal and thermal treatment: A review. *Journal of Food Quality*, 2022(1), Article 5797843. https://doi.org/10.1155/2022/5797843
104. Niu, D., Zeng, X.-A., Ren, E.-F., Xu, F.-Y., Li, J., Wang, M.-S. et al. (2020). Review of the application of pulsed electric fields (PEF) technology for food processing in China. *Food Research International*, 137, Article 109715. https://doi.org/10.1016/j.foodres.2020.109715
105. Khadhraoui, B., Ummat, V., Tiwari, B. K., Fabiano-Tixier, A., Chemat, F. (2021). Review of ultrasound combinations with hybrid and innovative techniques for extraction and processing of food and natural products. *Ultrasonics Sonochemistry*, 76, Article 105625. https://doi.org/10.1016/j.ultsonch.2021.105625
106. Katsaros, G., Taoukis, P. (2021). Microbial control by high pressure processing for shelf-life extension of packed meat products in the cold chain: Modeling and case studies. *Applied Sciences*, 11(3), Article 1317. https://doi.org/10.3390/app11031317
107. Li, R., Zhu, H., Chen, Y., Zhou, G., Li, C., Ye, K. (2022). Cold plasmas combined with Ar-based MAP for meatball products: Influence on microbiological shelflife and quality attributes. *LWT*, 159, Article 113137. https://doi.org/10.1016/j.lwt.2022.113137
108. Ulbin-Figlewicz, N., Brychcy, E., Jarmoluk, A. (2015). Effect of low-pressure cold plasma on surface microflora of meat and quality attributes. *Journal of Food Science and Technology*, 52, 1228–1232. https://doi.org/10.1007/s13197-013-1108-6
109. Valenzuela, C., Garcia-Galicia, I. A., Paniwnyk, L., Alarcon-Rojo, A. D. (2021). Physicochemical characteristics and shelf life of beef treated with high-intensity ultrasound. *Journal of Food Processing and Preservation*, 45(4), Article e15350. https://doi.org/10.1111/jfpp.15350
110. Aşık-Canbaz, E., Çömlekçi, S., Can Seydim, A. (2022). Effect of moderate intensity pulsed electric field on shelf-life of chicken breast meat. *British Poultry Science*, 63(5), 641–649. https://doi.org/10.1080/00071668.2022.2051431
111. Olaoye, O. A., Onilude, A. A. (2010). Investigation on the potential application of biological agents in the extension of shelf life of fresh beef in Nigeria. *World Journal of Microbiology and Biotechnology*, 26(8), 1445–1454. https://doi.org/10.1007/s11274-010-0319-5
112. Mohamed, E. F. E., Hafez, A. E.-S. E., Seadawy, H. G., Elrefai, M. F. M., Abdallah, K., Bayomi, R. M. et al. (2023). Irradiation as a promising technology to improve bacteriological and physicochemical quality of fish. *Microorganisms*, 11(5), Article 1105. https://doi.org/10.3390/microorganisms11051105
113. Pereira, R. N., Vicente, A. A. (2010). Environmental impact of novel thermal and non-thermal technologies in food processing. *Food Research International*, 43(7), 1936–1943. https://doi.org/10.1016/j.foodres.2009.09.013
114. Zhang, W., Naveena, B. M., Jo, C., Sakata, R., Zhou, G., Banerjee, R. et al. (2017). Technological demands of meat processing–An Asian perspective. *Meat Science*, 132, 35–44. https://doi.org/10.1016/j.meatsci.2017.05.008
115. Witrowa-Rajchert, D., Wiktor, A., Sledz, M., Nowacka, M. (2014). Selected emerging technologies to enhance the drying process: A review. *Drying Technology*, 32(11), 1386–1396. https://doi.org/10.1080/07373937.2014.903412
116. Mehmeti, A., Angelis-Dimakis, A., Arampatzis, G., McPhail, S., Ulgiati, S. (2018). Life cycle assessment and water footprint of hydrogen production methods: From conventional to emerging technologies. *Environments*, 5(2), Article 24. https://doi.org/10.3390/environments5020024

117. Sampedro, F., McAloon, A., Yee, W., Fan, X., Geveke, D. J. (2014). Cost analysis and environmental impact of pulsed electric fields and high pressure processing in comparison with thermal pasteurization. *Food and Bioprocess Technology*, 7(7), 1928–1937. https://doi.org/10.1007/s11947-014-1298-6
118. Yin, Y., Xu, H., Zhu, Y., Zhuang, J., Ma, R., Cui, D. et al. (2023). Recent progress in applications of atmospheric pressure plasma for water organic contaminants' degradation. *Applied Sciences*, 13(23), Article 12631. https://doi.org/10.3390/app132312631
119. Ajila, C. M., Brar, S. K., Verma, M., Prasada Rao, U. J. S. (2012). Sustainable solutions for agro processing waste management: An overview. Chapter in a book: Environmental protection strategies for sustainable development. Strategies for Sustainability. Springer, Dordrecht. 2012. https://doi.org/10.1007/978-94-007-1591-2_3
120. Javourez, U., O'donohue, M., Hamelin, L. (2021). Waste-to-nutrition: A review of current and emerging conversion pathways. *Biotechnology Advances*, 53, Article 107857. https://doi.org/10.1016/j.biotechadv.2021.107857
121. Sharma, P., Gaur, V. K., Sirohi, R., Varjani, S., Kim, S. H., Wong, J. W. C. (2021). Sustainable processing of food waste for production of bio-based products for circular bioeconomy. *Bioresource Technology*, 325, Article 124684. https://doi.org/10.1016/j.biortech.2021.124684
122. Aguirre-Garcia, Y. L., Nery-Flores, S. D., Campos-Muzquiz, L. G., Flores-Gallegos, A. C., Palomo-Ligas, L., Ascacio-Valdés, J. A. et al. (2024). Lactic acid fermentation in the food industry and bio-preservation of food. *Fermentation*, 10(3), Article 168. https://doi.org/10.3390/fermentation10030168
123. Zou, Y., Wang, L., Cai, P., Li, P., Zhang, M., Sun, Z. et al. (2017). Effect of ultrasound assisted extraction on the physicochemical and functional properties of collagen from soft-shelled turtle calipash. *International Journal of Biological Macromolecules*, 105, 1602–1610. https://doi.org/10.1016/j.ijbiomac.2017.03.011
124. Ikram, M., Ferasso, M., Sroufe, R., Zhang, Q. (2021). Assessing green technology indicators for cleaner production and sustainable investments in a developing country context. *Journal of Cleaner Production*, 322, Article 129090. https://doi.org/10.1016/j.jclepro.2021.129090
125. Chakka, A. K., Sriraksha, M. S., Ravishankar, C. N. (2021). Sustainability of emerging green non-thermal technologies in the food industry with food safety perspective: A review. *LWT*, 151, Article 112140. https://doi.org/10.1016/j.lwt.2021.112140
126. Mona, S., Kumar, S. S., Kumar, V., Parveen, K., Saini, N., Deepak, B. et al. (2020). Green technology for sustainable biohydrogen production (waste to energy): A review. *Science of the Total Environment*, 728, Article 138481. https://doi.org/10.1016/j.scitotenv.2020.138481
127. Muñoz, I., de Sousa, D. A. B., Guardia, M. D., Rodriguez, C. J., Nunes, M. L., Oliveira, H. et al. (2022). Comparison of different technologies (conventional thermal processing, radiofrequency heating and high-pressure processing) in combination with thermal solar energy for high quality and sustainable fish soup pasteurization. *Food and Bioprocess Technology*, 15(4), 795–805. https://doi.org/10.1007/s11947-022-02782-8
128. Houška, M., Silva, F. V. M., Evelyn, Buckow, R., Terefe, N.S., Tonello, C. (2022). High pressure processing applications in plant foods. *Foods*, 11(2), Article 223. https://doi.org/10.3390/foods11020223
129. Andreani, G., Sogari, G., Marti, A., Froldi, F., Dagevos, H., Martini, D. (2023). Plant-based meat alternatives: Technological, nutritional, environmental, market, and social challenges and opportunities. *Nutrients*, 15(2), Article 452. https://doi.org/10.3390/nu15020452
130. de Araújo, P. D., Araújo, W. M. C., Patarata, L., Fraqueza, M. J. (2022). Understanding the main factors that influence consumer quality perception and attitude towards meat and processed meat products. *Meat Science*, 193, Article 108952. https://doi.org/10.1016/j.meatsci.2022.108952
131. Young, E., Mirosa, M., Bremer, P. (2020). A systematic review of consumer perceptions of smart packaging technologies for food. *Frontiers in Sustainable Food Systems*, 4, Article 63. https://doi.org/10.3389/fsufs.2020.00063
132. Boz, Z., Korhonen, V., Koelsch Sand, C. (2020). Consumer considerations for the implementation of sustainable packaging: A review. *Sustainability*, 12(6) Article 2192. https://doi.org/10.3390/su12062192
133. Sievert, K., Lawrence, M., Parker, C., Baker, P. (2021). Understanding the political challenge of red and processed meat reduction for healthy and sustainable food systems: A narrative review of the literature. *International Journal of Health Policy and Management*, 10(12), Article 793. https://doi.org/10.34172/ijhpm.2020.238
134. Huang, H.-W., Hsu, C.-P., Wang, C.-Y. (2020). Healthy expectations of high hydrostatic pressure treatment in food processing industry. *Journal of Food and Drug Analysis*, 28(1), 1–13. https://doi.org/10.1016/j.jfda.2019.10.002
135. Meijer, G. W., Lähteenmäki, L., Stadler, R. H., Weiss, J. (2021). Issues surrounding consumer trust and acceptance of existing and emerging food processing technologies. *Critical Reviews in Food Science and Nutrition*, 61(1), 97–115. https://doi.org/10.1080/10408398.2020.1718597
136. Roh, T., Noh, J., Oh, Y., Park, K.-S. (2022). Structural relationships of a firm's green strategies for environmental performance: The roles of green supply chain management and green marketing innovation. *Journal of Cleaner Production*, 356, Article 131877. https://doi.org/10.1016/j.jclepro.2022.131877
137. Kubo, M. T., Baicu, A., Erdogdu, F., Poças, M. F., Silva, C. L., Simpson, R. et al. (2023). Thermal processing of food: Challenges, innovations and opportunities. A position paper. *Food Reviews International*, 39(6), 3344–3369. https://doi.org/10.1080/87559129.2021.2012789
138. Charlebois, S., Juhasz, M., Music, J., Vézeau, J. (2021). A review of Canadian and international food safety systems: Issues and recommendations for the future. *Comprehensive Reviews in Food Science and Food Safety*, 20(5), 5043–5066. https://doi.org/10.1111/1541-4337.12816
139. Manning, L. (2016). Food fraud: Policy and food chain. *Current Opinion in Food Science*, 10, 16–21. https://doi.org/10.1016/j.cofs.2016.07.001

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