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MEAT PROCESSING: A FOCUS ON QUALITY, FOOD SAFETY, AND SUSTAINABLE DEVELOPMENT

Hernández-Murillo Luz K.[1], Galán-Méndez Frixia[2*]

[1]*Universidad Nacional Abierta y a Distancia UNAD, Escuela de Ciencias Administrativas, Contables, Económicas y de Negocios – ECACEN & Escuela de Ciencias Básicas Tecnologías e Ingenierías ECBTI Ibagué, Tolima, Colombia.*
[2]*Universidad Veracruzana, Facultad de Ciencias Químicas, Xalapa, Veracruz, México.*

ABSTRACT

Access to meat products is limited in some regions of the world due to the scarcity of raw materials and production challenges, exacerbated by high energy consumption and livestock practices with negative environmental impacts. In this context, the aim of this study is to document the factors associated with thermal and non-thermal treatments used in the meat processing industry—specifically temperature, exposure time, and type of treatment—that significantly influence the quality of the final product. A mixed-method approach, both qualitative and quantitative, was employed, based on a systematic literature review (2009–2024) on thermal and non-thermal treatments used in the meat industry to enhance food safety. Advances in thermal and non-thermal technologies, such as ohmic heating and microwave cooking, have improved nutrient retention, reduced the formation of polycyclic aromatic hydrocarbons (PAHs), and optimized the organoleptic and nutritional quality of meat products.The preservation of meat products remains crucial, not only for extending their shelf life but also for reducing environmental impact through more sustainable practices. Thermal and non-thermal processes were identified that ensure food safety, from the preservation of raw materials to the final product, using the cold chain. In conclusion, improvements in thermal and non-thermal treatments increase productivity, yield, and the quality of meat products, reducing losses and contributing to the Sustainable Development Goals: Zero Hunger and Responsible Consumption and Production.

Keywords— meat, meat products, thermal and non-thermal processes, food safety, zero hunger.

Introduction

Meat and meat products stand out as essential sources of nutrients such as proteins, essential amino acids, polyunsaturated fatty acids, vitamins, and minerals that are indispensable for human nutrition (Ordaz-Rodríguez *et al.,* 2022; Vinnikova*et al.,* 2019). According to the Food and Agriculture Organization of the United Nations (FAO), more than one billion people worldwide depend on livestock value chains for their livelihoods (FAO, 2023). However, to meet the growing demand for meat, producers have adopted intensive production methods, which involve significant resource use, such as water, deforestation, and the application of agrochemicals (Díaz & Jiménez, 2024). This context presents a global challenge for the meat industry, which must balance the need to transform raw materials into meat products with environmental sustainability throughout the production process.

Meat products pose a high public health risk due to their nutritional composition, rich in proteins and fats, which provides a conducive environment for the proliferation of pathogenic microorganisms (Rabelo *et al.,* 2024). The implementation of adequate preservation methods is essential to prevent food spoilage and minimize associated risks (Guerrero *et al.,* 2023). When food is treated with conventional technologies, such as pasteurization and sterilization, it is exposed to high temperatures to extend its shelf life, reducing microbial load but also affecting the sensory and nutritional quality of the products (Ekonomou&Boziaris, 2021; Jadhav *et al.,* 2021). Consumer demand for foods with excellent sensory, nutritional, and microbiological characteristics has posed a challenge in producing products that meet these criteria. Therefore, with the rise of emerging technologies, non-thermal treatments can be applied to achieve foods with higher quality and longer shelf life. By avoiding heat, microorganisms can be inactivated with minimal alteration to sensory and nutritional characteristics if appropriate processing parameters are used (Jadhav *et al.,* 2021; Targino*et al.,* 2021).

Thus, the significant contribution of meat to global nutrient availability underscores its crucial role in feeding the current global population (Smith *et al.,* 2022). Finally, the recognition of meat's vital role in human nutrition by the United Nations highlights its importance as a key element in achieving the Sustainable Development Goals (Smith *et al.,* 2022).

1. Importance of meat consumption

Meat is defined as the edible muscular part of food animals that have been slaughtered and dressed under hygienic conditions. This definition includes portions of fat, bone, cartilage, skin, tendons, aponeurosis, nerves, and lymphatic and blood vessels that accompany the muscle tissue and are not separated during handling, preparation, and processing.

After slaughter, a maturation process is essential, the duration and conditions of which depend on the species. For beef, a maturation period of 7 days is recommended; for pork, 3 days; and for poultry, 12 hours, all at a temperature of 6°C. This natural biochemical process transforms the muscle, composed primarily of muscle fibers, collagen, and fat, into meat suitable for human consumption (Horcada&Polvillo, 2010).

The maturation process imparts specific organoleptic and physicochemical characteristics to the meat, such as the characteristic red color in beef. During maturation, the muscles relax, resulting in more tender meat. Enzymes present in the meat break down proteins into smaller units, improving flavor and digestibility. Additionally, the increase in lactic acid, derived from the animal's glucose and fat, contributes to an enhanced aroma (Guerrero *et al.,* 2023). Figure 1 shows the various shades of color in meat and meat products, reflecting the transformation and innovation applied for their commercialization in supermarket chains.

Figure 1. Meat and meat products (Source: Own elaboration, 2024).

According to González *et al*. (2020), meat consumption has shown a steady increase in most countries since the 1960s, with more pronounced growth starting in the 1980s up to the present day. Three categories have been identified that influence meat consumption: eating habits, human health, and climate change (Table 1). Each of these categories is linked to the consumption behavior observed in different regions of the world.

Table 1. Factors influencing meat product consumption.

Category	Variables found in the study	Product	Regions
Eating habits	Increase in consumption due to market availability	Pork	Southeast Asia
		Poultry	North America
	It accounts for approximately 30% of the total caloric intake of the diet. This percentage corresponds to an average intake of 28 grams of protein per person per day	Meat products	Europe
Human health	Its consumption should be reduced to below 50g/day to avoid an increased risk of prostate cancer, breast cancer, or colorectal cancer	Red meat	International
	It is evident that they contain lower amounts of environmental contaminants and the risk of developing carcinoma is reduced by up to 39%	White meat	
Climate change	The quality of meat is affected by the potential effects of climate change on the increase of pathogenic microorganisms (*Escherichia coli* or *Salmonella*) present during transportation	Meat products	International

Source: Own elaboration based on González *et al.*, 2020.

1.1. Nutritional composition

Food safety involves controlling parameters that determine the quality of meat, ensuring that it is safe for direct consumption after cooking as well as for its transformation into meat products. Figure 2 highlights the factors that should be considered when purchasing meat for a balanced diet. Additionally, Wang *et al.* (2024), recommend a daily protein intake of 0.8 to 1.0 g/kg of body weight for individuals in good physical condition, and 1.0 to 1.2 g/kg of body weight for older adults.

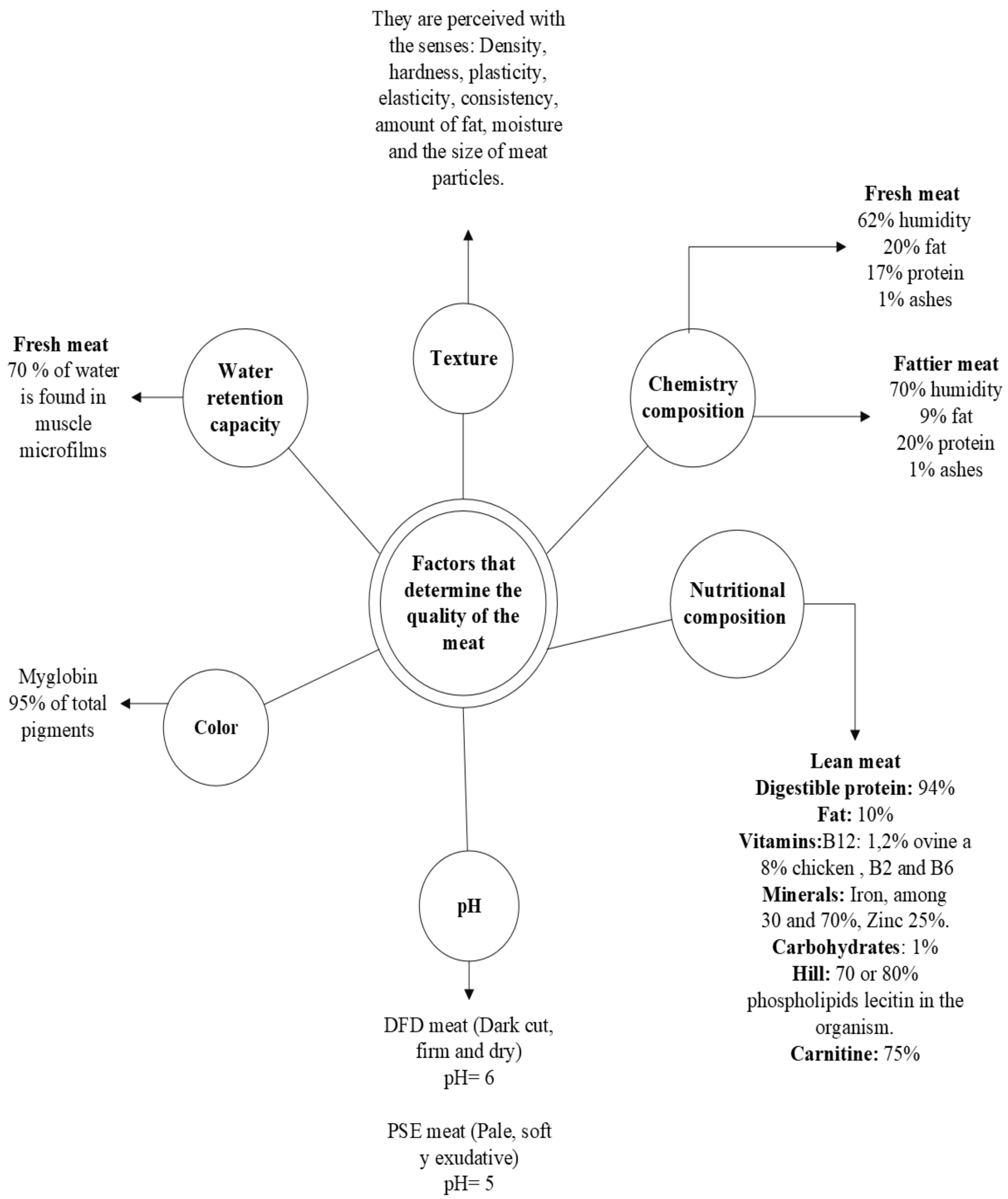

Figure 2. Factors influencing meat quality (Source: Own elaboration based on

Horcada&Polvillo, 2010; Andújar, 2009).

1.2. Food scarcity associated with meat

Meat is one of the foods whose consumption varies significantly worldwide and provides a range of essential macronutrients and micronutrients, including proteins, fats, carbohydrates, essential fatty acids, iron, calcium, zinc, selenium, vitamin B1, choline, and bioactive compounds such as carnitine, creatine, and taurine. Protein is an essential nutrient that provides the amino acids necessary for normal human growth and development. In particular, red meat offers a broader range of amino acids, which are more easily digested compared to plant-based proteins. Moreover, sources of red meat are often rich in micronutrients that play a crucial role in various essential bodily functions (FAO, 2023; Clonan *et al.*, 2015).

It is important to note that meat is classified into four categories based on species, production processes, and the acquisition of by-products suitable for human consumption, as shown in Figure 3.

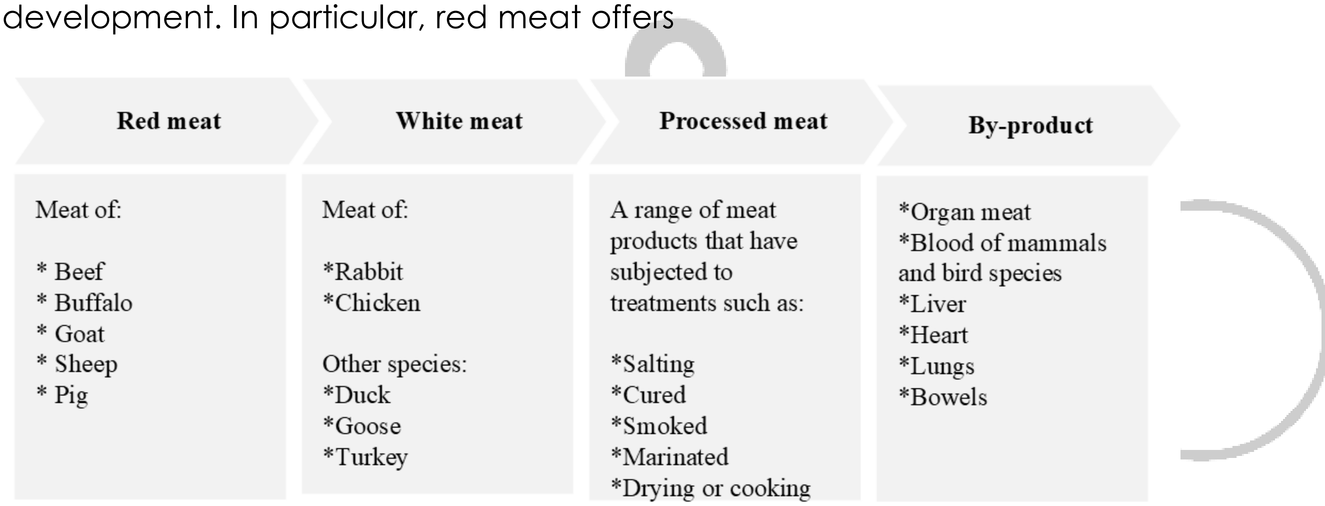

Figure 3. Classification of meat and meat products (Source: Own elaboration based on FAO, 2023).

Due to the above, there is a wide variety of animals raised for slaughter and suitable for meat consumption, depending on the species chosen. Díaz and Jiménez (2024) assert that the globalization of the supply chain has involved the importation of meat from various parts of the world, contributing to the carbon footprint associated with the long-distance transportation of food. However, this marketing practice, which involves the export of meat between countries, generates two significant impacts: the first is environmental, due to the pollution produced during transportation; the second is economic, as it does not promote local trade, negatively affecting farming families and micro and small enterprises in the region.

On the other hand, the FAO (2023) highlights that there is a considerable global shortage of micronutrients, such as iron and vitamin A. It is estimated that more than one in two preschool children (372 million) and 1.2 billion women of reproductive age lack at least one of these three micronutrients: iron, vitamin A, or zinc. Three-quarters of these children reside in South and East Asia, the Pacific, and Sub-Saharan Africa. Although there are few populations where meat is not part of the average diet, its consumption is expected to increase in the next 10 years, particularly in developing countries (Smith *et al.,* 2022).

Consequently, one of the most significant constraints in the livestock production chain lies in the reactive management of reproductive, infectious, deficiency, metabolic, and parasitic diseases. Additionally, it is crucial to implement mitigation and adaptation measures for climate change due to the high influence of this factor on production (Orjuela *et al.,* 2020).

2. Good production practices

Due to the various handling processes that meat undergoes before reaching the final consumer, it is essential to implement process controls in plants to ensure the quality and safety of the product (Orjuela *et al.,* 2020). In the food sector, thermal methods, known as thermal treatments, are the most commonly used. These procedures aim to partially or completely destroy the microbial population present in foods (Muñoz, 2023).

The primary objective of these treatments is to chemically and biochemically transform the constituents of the meat to make them more easily digestible, as is the case with the denaturation of proteins, which is often accompanied by partial gelatinization. Secondly, a radical transformation of the organoleptic properties of the products occurs, improving chewing tenderness and developing pleasant aroma and flavor, which contributes to a more enjoyable consumption experience. Finally, thermal treatments serve as a preservation method, enhancing safety during consumption, reducing health risks, and simultaneously extending the shelf life of meat products (Andújar, 2009).

2.1. Traditional thermal processes

Thermal treatment refers to the heating of food to a specific temperature for a determined period. This process is common in most meats and meat products, which are almost always subjected to some type of thermal treatment before consumption. Traditional cooking methods, such as boiling and baking, have been widely used since ancient times (Hassoun *et al.,* 2021). The choice of an appropriate thermal treatment for meat is crucial to keep the food viable for consumption over extended periods, ensuring the complete destruction of present microorganisms, as occurs in sterilization.

In ready-to-eat meat products, pasteurization techniques are applied, which, although they do not eradicate resistant forms of microorganisms, are effective in inhibiting the proliferation of pathogens. This method guarantees food safety, provided that the consumption limit indicated by the expiration date is respected.

For example, thermal treatment by heat, such as smoking (Table 2), not only preserves the meat but also imparts specific odors and flavors. Additionally, cold preservation thermal treatments, as shown in Table 3, are also of great relevance (Muñoz, 2023). Finally, the combination of thermal treatments by both heat and cold during the transformation process of meat products is fundamental, as illustrated in Figure 4.

Table 2. Heat treatment in the smoking process.

Methods	Control temperature	Effect
Internal cooking	62 - 64 °C	Cooking is insufficient, and microorganisms remain.
Pasteurization	68 – 72°C	Depending on the type of cooking, *trichina* (a microorganism present in infected pork that is cooked for a short time) can be destroyed. The nutritional value is maintained, as well as most organoleptic characteristics.
Sterilization	110 -120°C	It eliminates all bacterial forms, and the resulting products have a long shelf life. A disadvantage of this method is the alteration of organoleptic qualities, such as the disintegration of muscle tissue and the loss of vitamins, among others.

Source: Own elaboration based on Muñoz, 2023; Hassoun *et al.*, 2021.

Table 3. Cold thermal treatments.

Method	Principle of conservation	Control variable
Refrigeration	Maintain the organoleptic characteristics of the food and its hygienic quality. At this temperature, the growth of thermophilic and mesophilic microorganisms is prevented.	Temperature: 0 a 8 °C

Freezing	It is based on the cooling of the water containing the food until it transitions to a solid state. This halts the bacteriological and enzymatic processes that occur during the decomposition of the meat.	Temperature: 0 a -18 °C

Source: Own elaboration based on Muñoz, 2023; Hassoun *et al.*, 2021.

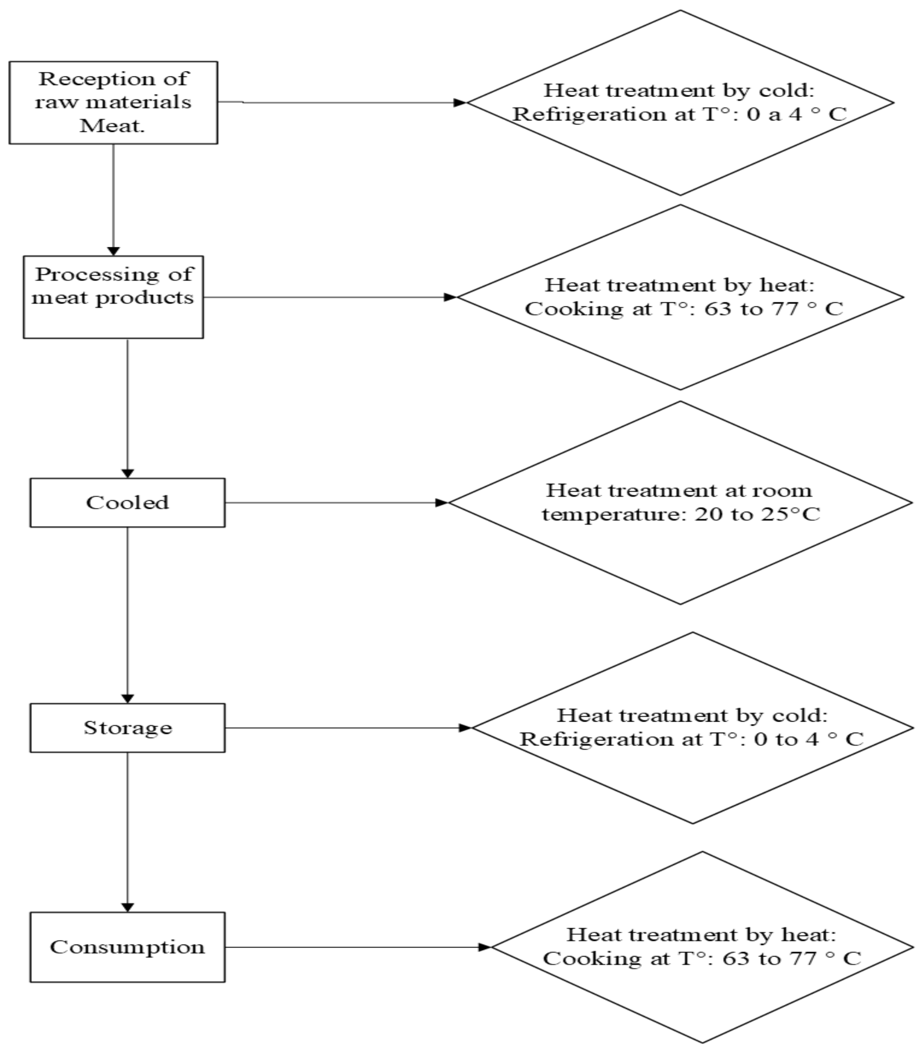

Figure 4. Combined thermal treatments during the process (Source: Own elaboration).

2.2.Problems of thermal treatment of meat products

Thermal treatment is an essential part of the processing and preparation of meat and meat products. Generally, cooking causes the denaturation, aggregation, and chemical modifications of meat proteins, affecting the structural (micro, quaternary, tertiary, and even secondary) and functional properties of muscle proteins. These changes induce alterations in protein digestion, their destinations, and various metabolic activities (Wang *et al.*, 2024). However, excessive heating can lead to undesirable changes in the chemical composition of the product, resulting in a decrease in its quality and biological value, deterioration of organoleptic parameters, as well as an increase in mass loss (Vinnikova*et al.*, 2019). Table 4 shows the most significant effects of protein denaturation, and Figure 5 illustrates the effects on myosin protein as the temperature increases.

Table 4. Physicochemical changes in meat during thermal treatment.

Effect	Cause	Result
Physicochemicalchange	Thermal denaturation of protein substances; boiling and hydrothermal decomposition of collagen; changes in extractive substances and vitamins; changes in structural and mechanical properties, moisture retention capacity; formation of flavor and aroma components; color change; loss of product components to the environment; death of microbiota.	The meat acquires new flavors, typical aromatic properties, and a dense and easily digestible consistency for the stomach.
Denaturing effect of heat on proteins	The thermal denaturation of muscle proteins begins at a temperature of 30 to 35°C. When heated to 60-65°C, approximately 92% of the salt-soluble proteins and up to 93% of the water-soluble intracellular proteins denature, but even at a temperature of 100°C, a small amount of protein substances remains in their native state.	Heat-denatured proteins easily aggregate and coagulate, consolidating with the release of water.

Source: Own elaboration based on Wang *et al.*, 2024; Vinnikova*et al.*, 2019.

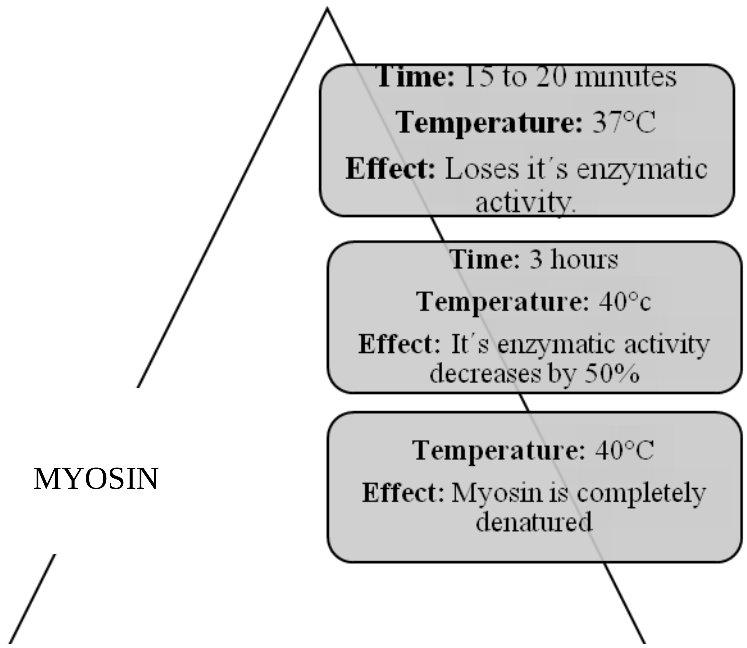

Figure 5. Cause-effect behavior in the temperature and time of denaturation of the main heat-sensitive meat protein: myosin(Source: Own elaboration based on Vinnikova, 2019).

2.3.Innovations in thermal process control to improve the quality of the final product

Given the global increase in the consumption of meat products, consumers demand foods that not only offer high nutritional value (including proteins, fatty acids, and minerals) but also superior flavor and aroma after cooking (Xu *et al.*, 2021). In response to these demands, Table 5 presents two emerging thermal processing technologies, and Table 6 presents two non-thermal processing technologies that have been developed to improve the quality and nutritional value of meat products.

Table 5. Thermal processing technologies in meat products.

Technology	Definition	Product	Variables	Nutricional value
Microwave	It is a dielectric heating technology that utilizes electromagnetic wave energy in the frequency range of 0.3 to 300 GHz. The basic dielectric properties of food materials are expressed as ε* = ε ' - jε ”, where j = √-1. ε ' represents the ability to store microwave energy, while ε”	Chicken thigh	Microwave; 180 W for 10 min	Greater water retention capacity; firmer texture.
		Horse meat	Microwave; 1000 W for 1,5 min	Lower water retention capacity; higher values of brightness and yellowness; firmer texture; greater cooking loss.

	represents the ability to convert microwave energy into heat.	Pork belly	Microwave combined with conduction heating; 800 W for 100 s and 400 W for 200 s, continuously for 300 s.	Greater water retention capacity; lower cooking loss; improved tenderness.
Ohmic	It is an electric heating technology, operating in the range of 0.01 to 10 S/m (25 °C). Its effectiveness in meat products depends on the orientation of the electric field, temperature, and the composition of the food material, such as fat content, salt content, and fiber orientation.	Beef	Ohmic; 12 V/cm, 3.3 V/cm, 72 °C	Lower cooking loss; improved tenderness; enhanced color.
		Meatball	Ohmic; 4.9 °C/min and 24.5 °C/min	Greater resistance to yield strength.

Source: Own elaboration based on Xu *et al.*, 2021.

Table 6. Non-thermal processing technologies in meat products.

Technology	Definition	Product	Variables	Nutritional value
Pulsed Electric Fields (PEF)	It is based on the electric field process that induces modifications in the food membrane structure and enhances mass transfer, but without any detrimental effects on its attributes. The food materials are placed between two electrodes and then treated with a short-duration electric field pulse (1–100 μs) with an electric field intensity (100–300 V/cm, or 20–80 kV/cm).	Beef	1,4 kV/cm, 10 Hz, 20 μs	Improvement of sensitivity.
		Beef	0,8–1,1 kV/cm, 50 Hz, 20 μs, 130 kJ/kg	Improvement of sensitivity; higher redness value.
Ultrasound	It is a longitudinal mechanical wave that vibrates between frequencies of 20 kHz and 10 MHz. Due to its high intensity (10–1000 W/cm²), it can generate free radicals and reactive	Chicken breast	40 kHz, 22 W/cm 2, 15–30 min	Improvement of mass transfer.

	oxygen species (which implies mass transfer and chemical reactions) through stable and transient cavitation, leading to lipid oxidation and protein denaturation in meat products. Similar to PEF, the effect of ultrasound technology on meat products primarily acts on the activation of calpain activity, inducing high-intensity denaturation of myosin. Additionally, ultrasound applied to meat products can result in high rates of salt and water diffusion.	Cured pork	37 kHz, 22 W/cm 2, 30–90 min	Improvement of saltiness perception; decrease in color saturation; no significant influence on other cooking loss values.
		Rabbit loin	24 kHz, 12 W/cm 2, 15 min	Lower water retention capacity; lower shear force; higher brightness and yellowness.
High Hydrostatic Pressure	It is a novel, non-thermal, and eco-friendly method. It has been widely applied in the food industry, particularly in meat products. This method involves immersing food in a liquid medium (e.g., water) subjected to pressures ranging from 100 MPa to 1000 MPa at room temperature. Pressures below 300 MPa can produce high levels of active flavor compounds, while pressures exceeding 300 MPa can lead to the oxidation of proteins and lipids associated with aromatic compounds.	Dry-cured ham	600 Mpa	Increase in chewiness and hardness; decrease in color intensity.
		Chicken breast	300–600 Mpa	Improvement of sensitivity.

Source: Own elaboration based on Xu *et al.*, 2021.

2.4.Innovative approach for the reduction of polycyclic aromatic hydrocarbons (PAHs)

The thermal processing of meat products, which includes traditional and modern methods such as smoking, grilling, baking, and roasting, is influenced by a variety of factors that contribute to the formation of polycyclic aromatic hydrocarbons (PAHs). These factors include the type of meat used, cooking time and temperature, the distance between the food and the heat source, the chemical composition of the food, the water activity, as well as the type of fuel and smoke employed (Das *et al.*, 2023). PAHs are organic compounds characterized by at least two aromatic rings bonded together. They are fat-soluble and have chemical stability, being classified as carcinogens for humans (Hokkaido *et al.*, 2018).

To mitigate the formation of PAHs, it is essential to optimize cooking and processing conditions during the thermal treatment of meat products. In this regard, Hokkaido *et al*. (2018) emphasize that, without compromising microbiological safety, the use of indirect smoking—with a distance of over five meters between the food and the smoke source—along with smoking times of less than five hours and optimized temperatures, can be effective in reducing PAHs levels in fish and meat products.

Additionally, it is recommended to combine thermal treatments with innovative approaches, such as the use of filters and adsorbents in the smoking process, plant-derived antioxidants, and marinades rich in phenolic compounds. Bioelimination processes have also been explored through the application of lactic acid bacteria and probiotics as strategies to reduce PAHs formation (Das *et al*., 2023).

2.5. Study on nutrient retention and improvement of flavor and texture

The thermal treatment of meat products can impart organoleptic qualities that make them more appealing to consumers (Muñoz, 2023). The meat industry has experienced significant growth in recent years, partly due to the growing evidence that these thermal treatments induce microstructural changes that enhance the functional properties of meat (Baldi *et al.,* 2021). Meat plays a crucial role in the global availability of nutrients, standing out in providing nutrition to the current world population (Smith *et al.,* 2022).

During the heating of meat, specific flavor and aroma arise from the interaction between amino acids and carbohydrates, particularly through the Maillard reaction, in which sugars and amino acids react to form flavor compounds (Vinnikova*et al.,* 2019). An example of this phenomenon is the formation of flavor compounds during the ultrasound-assisted curing process. Ultrasound has shown significant potential for enhancing flavor by effectively optimizing the organoleptic characteristics of cured meat (Biao *et al.,* 2024) (Table 7).

Table 7. Effects of microwave-assisted curing.

Effect	Concept
Tenderness	The tenderness of meat products is a crucial attribute that is influenced by the composition, structural organization, and integrity of the skeletal muscle.
Waterretentioncapacity (WRC)	It is the intrinsic capacity of muscle tissues to maintain their initial levels of hydration and to undergo osmotic processes to acquire additional water when subjected to external influences, such as compressive forces, freezing, and

	thawing.
Flavor	The degradation of water-soluble and fat-soluble precursors in meat is the main source of volatile flavor compounds. These precursors, such as amino acids and fatty acids, play a crucial role as pre-flavor substances. The content and type of amino acids and fatty acids, along with the subsequent reactions they undergo, significantly affect the flavor of meat.

Source: Own elaboration based on Biao *et al.*, 2024.

2.6. Evaluation of the impact on microbiological safety

The optimization of thermal treatments has a significant positive impact on the microbiological safety of meat products by reducing the presence of pathogens that can cause product spoilage and illness in consumers (Muñoz, 2023). Ambient temperature is a crucial factor that influences the capacity and intensity of microorganism development. Each microorganism has a specific temperature range in which it can grow, including a minimum, optimum, and maximum temperature. The minimum temperature is the one below which microbial growth does not occur; the optimum temperature is ideal for microbial development; and the maximum temperature is the one above which microbial growth ceases (Vinnikova*et al.,* 2019).

Meat products are considered high risk for public health due to their nutritional composition, which is rich in proteins and fats, providing a favorable environment for the proliferation of pathogenic microorganisms (Rabelo *et al.,* 2024). Therefore, proper management of thermal treatments is essential to ensure microbiological safety and reduce the risks associated with microbial contamination in these products.

2.7. Emerging technologies such as ohmic heating and microwave cooking

The technological properties of meat, such as water retention capacity, as well as its emulsifying and gelling properties, are receiving increasing attention due to their importance in the food industry. The application of innovative technologies is positioning itself as one of the most promising options for improving these properties (Baldi *et al.,* 2021).

Meat products provide a nutrient-rich matrix and a conducive environment for the proliferation of microorganisms that can spoil the meat and transmit common pathogens. In this context, ohmic heating emerges as a promising alternative technology. This method is based on the application of electric current through the meat product, generating internal heat that inactivates microorganisms through thermal mechanisms (Yildiz-Turp*et al.,* 2013).

Additionally, microwave cooking is another emerging technology that has shown benefits in improving the properties of meat products. Both technologies offer significant potential to optimize microbiological safety and enhance the organoleptic quality of meat, contributing to efficiency and safety in the processing of meat products.

3. Preservation of meat products

The objective of preservation methods is to prevent the mechanisms that cause food spoilage by using specific techniques designed to extend shelf life and maintain quality (Guerrero *et al.*, 2023). Preservation is a crucial aspect of the quality of meat products, which is determined by three main factors (Muñoz, 2023):

- Raw material: The quality of the meat product is influenced by the animal, considering variables such as species, breed, sex, age, and diet.
- Method of obtaining: This includes the way in which the animal is slaughtered, a fundamental factor that affects the initial quality of the meat.
- Processing: This refers to the stages after slaughter, which include obtaining the carcass, cutting, and producing meat products.

A high-quality meat product is one that is healthy, nutritious, and organoleptically pleasant. According to these criteria, the quality of the product can be classified into three types, as explained in Table 8.

Table 8. Types of quality in the meat industry.

Tipo de Calidad	Concepto	Control
Hygienic	It is affected by types of biological, chemical, and physical contaminants.	Biological: The microorganisms of greatest interest in meat products are *Clostridium botulinum*, *Salmonella*, *Listeria*, and *Staphylococcus aureus*. Chemical: The use of undesirable chemical agents such as nitrates and nitrites. Physical: Solid products resulting from poor handling, for example, wood splinters from pallets or labeling residues.
Nutritional	It depends on the chemical composition of the food. The nutritional contribution of these products consists of proteins and essential amino acids.	It can be affected by thermal treatments and prolonged storage.
Sensory	To attract consumers, the product qualities must be pleasing to them so that they are willing to pay for them.	Attributes such as appearance (shape, size, color, etc.), texture (hardness, juiciness, fibrousness, creaminess, fattiness, gelatinous or elastic character), flavor (salty, sweet, or bitter), and odor (in addition to the characteristic aroma of each product, given by flavor, which consists of a combined perception of aroma and taste) influence it.

Source: Own elaboration based on Muñoz, 2023.

Although meat is a perishable product, it is essential to maintain it at appropriate temperatures to preserve its organoleptic qualities and minimize the main causes of spoilage. These causes include the natural proliferation of microorganisms (such as spores, bacteria, molds, and yeasts), the action of environmental agents (water, air, humidity, heat, cold), chemical and biochemical reactions (such as ripening), as well as attacks by insects, pests, and rodents (Guerrero *et al.,* 2023).

Temperature control is fundamental to reducing bacterial spoilage of meat products, as low temperatures decrease microorganism activity. To ensure food safety, refrigeration and freezing systems must be monitored rigorously. In the case of refrigeration, the temperature must be kept below 10 °C. For freezing, raw meats should be stored at -18 °C, while cooked meats should be stored at -12 °C. These parameters ensure that meat products remain within a safe temperature range (Muñoz, 2023). The preservation of meat and meat products in the cold chain is illustrated in Figure 6.

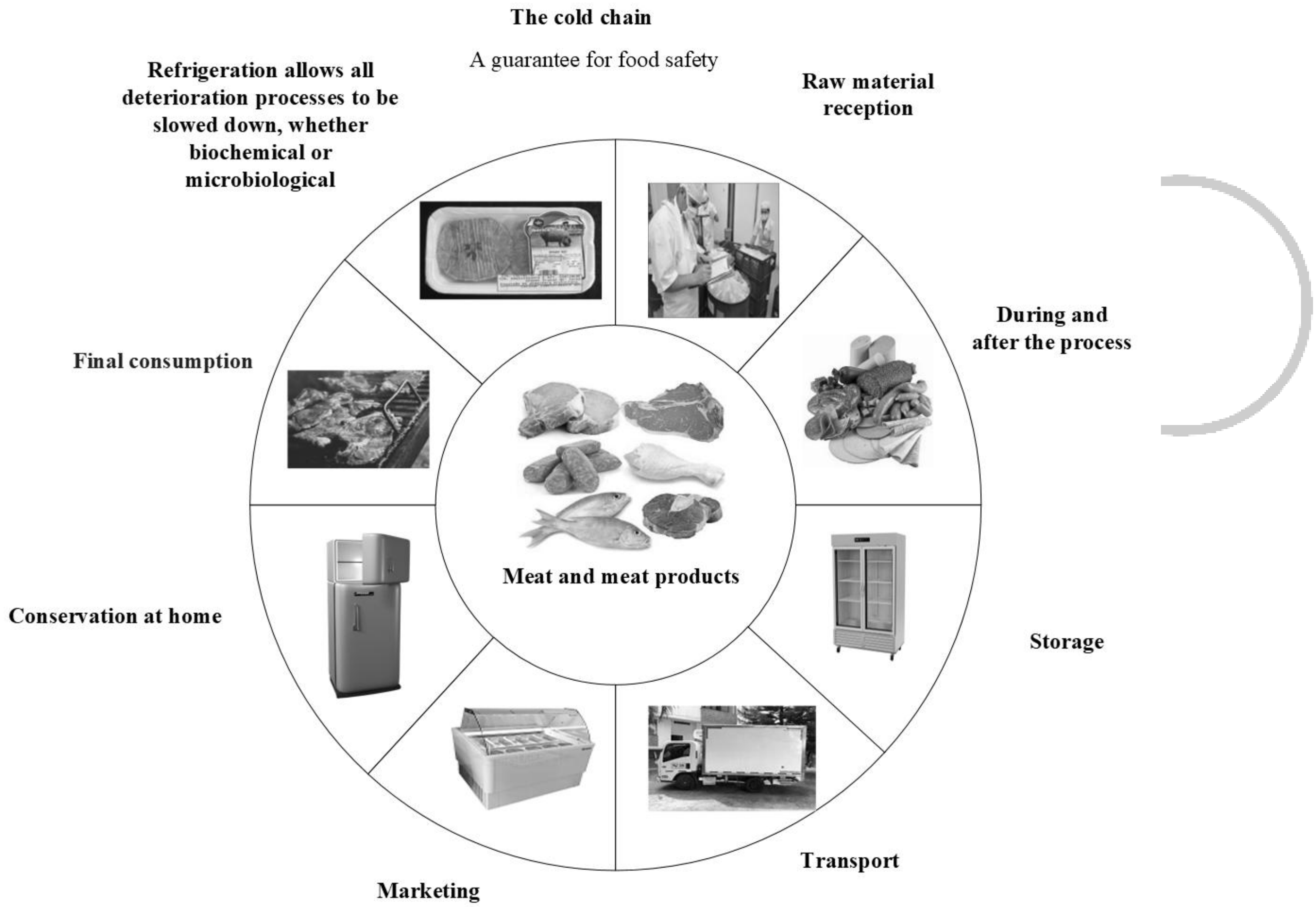

Figure 6. Non-thermal treatments used in the traceability of meat and meat product preservation in the cold chain. (Source: Own elaboration).

4. Sustainable environmental impact

In the modern era, meat consumption is widespread, and consumers must consider not only personal and family health but also the environmental footprint associated with their diet and animal welfare (Clonan, 2015). Meat plays a crucial role in human nutrition, being recognized by the United Nations as a fundamental component for sustainability and for achieving the Sustainable Development Goals (Smith *et al.,* 2022). However, the meat industry exerts a significant impact on the environment, both due to the presence of its facilities in habitats of plant and animal species and the emissions of substances or gases derived from production processes (Muñoz, 2023).

In this context, the appropriate use of by-products from the meat industry can represent a sustainable development initiative. Reusing these by-products as food additives not only helps mitigate environmental issues but also contributes to improving human health by enriching meat and its derivatives with beneficial substances such as phenols, dietary fibers, and vitamins (Ordaz-Rodríguez *et al.,* 2022).

Furthermore, alternative techniques for treating meat products are designed to be gentle, energy-efficient, environmentally friendly, and to provide excellent appearance and flavor while eliminating pathogenic microorganisms and the microbiota that causes product spoilage (Vinnikova*et al.,* 2019). The waste generated during the production of meat products can be classified according to its nature, as detailed in Table 9, which divides them into three types: solids and packaging, liquids, and emissions to the atmosphere.

Table 9. Types of waste generated in the meat industry.

Typeofwaste	Source	Generatedwaste
Solids and packaging	Organic matter from animals, such as manure and tissue remnants. On the other hand, the material used in the packaging and wrapping of products.	Organic solid: Hair/wool, feathers, entrails, and intestinal contents. Inorganic solid: Typically made of steel and plastic material.
Liquiddischarges	Liquid waste includes blood and other bodily fluids, as well as wastewater contaminated by solid waste.	Blood, if collected hygienically, can be used in human food or, alternatively, in other products such as blood meal for animal feed.
Emissionstotheatmosphere	The machinery used typically operates on electrical energy, which does not generate gases or fumes; however, there are certain equipment where combustion is necessary, such as wood-fired ovens, smoking equipment, and emissions from boilers used to generate steam.	Odors emanating from live animals in slaughterhouses, digestive contents, and dust pollution. In refrigerants, the use of chlorofluorocarbons (CFCs) and hydrofluorocarbons (HFCs), which, when released into the atmosphere, are affected by UV radiation, leading to the release of chlorine responsible for ozone depletion.

Source: Own elaboration based on Muñoz, 2023.

Finally, throughout the entire production process in the meat industry, there is a high energy consumption due to the stages of processing, thermal preservation treatments, packaging, and storage (refrigeration and freezing). These stages mainly depend on electrical energy and fossil fuels, which are the primary sources for these processes. The use of these non-renewable energy sources generates a significant amount of greenhouse gases, especially carbon dioxide, contributing to global warming, a phenomenon widely recognized today (Muñoz, 2023).

5. Future directions for research and development

Global trends in beef consumption present significant opportunities for the market, including aspects related to health and the environment, labeling, meat substitutes, lab-grown meat, the increasing demand for high-value animal proteins, and a greater demand for breakfasts that incorporate meat, as well as vegan diets (Orjuela *et al.,* 2020).

Areas of interest for the scientific community include sensory analysis of beef, animal feed, processed products, practices in processing plants, transport of carcasses, the use of by-products from the animal processing, and packaging systems (Orjuela *et al.,* 2020). An example of innovation in the processing of meat products is the use of ultrasonic technology, which has been noted for its high efficiency and environmental friendliness, significantly improving numerous processes in the food industry (Biao *et al.,* 2024).

Future research should focus on these emerging trends and advanced technologies to address the challenges and opportunities they present, aiming to improve the quality, sustainability, and safety of meat products.

Conclusions

As a result of the literature review, it is concluded that meat, being a perishable food, requires the implementation of traceability systems and the application of appropriate thermal processes in the meat industry, with a primary focus on food safety. The optimal preservation of raw materials and their derived products, through a continuous cold chain, is essential to ensure food safety. Advances in thermal treatments not only ensure the quality and safety of meat products but also contribute to improving their availability by reducing losses during processing and consumption, significantly supporting the achievement of Sustainable Development Goal (SDG) 2: Zero Hunger.

On the other hand, recognizing the environmental impacts of the meat industry is essential, as a significant portion of the waste generated is organic matter that can be reused to add value, which aligns with Sustainable Development Goal (SDG) 12: Responsible Production and Consumption. These practices not only promote a more sustainable approach to the management of meat by-products but also represent an opportunity to reduce the environmental footprint of the industry, contributing to a more sustainable future.

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