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EDITED BY
Tong Xing,
Nanjing Agricultural University, China

REVIEWED BY
Xing Chen,
Jiangnan University, China
Chao-Kun Wei,
Ningxia University, China

*CORRESPONDENCE
Aristide Maggiolino
✉ aristide.maggiolino@uniba.it
Muhammad Sajid Arshad
✉ msajidarshad@gcuf.edu.pk

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Dynamic alterations in protein, sensory, chemical, and oxidative properties occurring in meat during thermal and non-thermal processing techniques: A comprehensive review

Waseem Khalid[1], Aristide Maggiolino[2]*, Jasmeet Kour[3], Muhammad Sajid Arshad[1]*, Noman Aslam[1], Muhammad Faizan Afzal[1], Parkash Meghwar[4], Khair-ul-Wajeeha Zafar[5], Pasquale De Palo[2] and Sameh A. Korma[6,7]

[1]Department of Food Science, Faculty of Life Sciences, Government College University, Faisalabad, Pakistan, [2]Department of Veterinary Medicine, University of Bari Aldo Moro, Bari, Italy, [3]Department of Food Science and Technology, Padma Shri Padma Sachdev Government PG College for Women, Jammu, Jammu and Kashmir, India, [4]Department of Food Science and Technology, University of Karachi, Karachi, Pakistan, [5]Department of Chemistry, Government College University, Faisalabad, Pakistan, [6]Department of Food Science, Faculty of Agriculture, Zagazig University, Zagazig, Egypt, [7]School of Food Science and Engineering, South China University of Technology, Guangzhou, China

Meat processing represents an inevitable part of meat and meat products preparation for human consumption. Both thermal and non-thermal processing techniques, both commercial and domestic, are able to induce chemical and muscle's proteins modification which can have implication on oxidative and sensory meat characteristics. Consumers' necessity for minimally processed foods has paved a successful way to unprecedented exploration into various novel non-thermal food processing techniques. Processing of meat can have serious implications on its nutritional profile and digestibility of meat proteins in the digestive system. A plethora of food processing techniques can potentially induce alterations in the protein structure, palatability, bioavailability and digestibility *via* various phenomena predominantly denaturation and Maillard reaction. Apart from these, sensory attributes such as color, crispness, hardness, and total acceptance get adversely affected during various thermal treatments in meat. A major incentive in the adoption of non-thermal food processing is its energy efficiency. Considering this, several non-thermal processing techniques have been developed for evading the effects of conventional thermal treatments on food materials with respect to Maillard reactions, color changes, and off-flavor development. Few significant non-thermal processing techniques, such as microwave heating, comminution, and enzyme addition can positively affect protein digestibility as well as enhance the value of the final product. Furthermore, ultrasound, irradiation, high-pressure processing, and pulsed electric fields are other pivotal non-thermal food processing technologies in meat and meat-related products. The present review examines how different thermal and non-thermal processing techniques, such as sous-vide, microwave, stewing, roasting, boiling, frying, grilling, and steam cooking, affect meat proteins, chemical composition, oxidation, and sensory profile.

KEYWORDS

meat, thermal processing, non-thermal processing, protein changes, sensory changes

1. Introduction

Meat has an exceptionally rich nutritional value and serves as an excellent source of several essential amino acids and various micronutrients such as vitamins B_3 and B_{12}, iron, and zinc (1). Meat has been classified into three main categories: red meat, poultry, and seafood. Entire livestock is constituted under red meat including lamb, beef, pork, and goat. Poultry usually refers to white meat that constitutes chicken while fish, crustaceans (viz. crab, lobster) and mollusks (viz. clams, oysters, scallops, mussels) comprise of seafood (2). Muscle, and consequently meat chemical composition, is characterized by a great water content (∼75%) followed by protein (∼20%), fat (∼3%), and soluble non-protein substances (∼2%), with differences among different species considered (3–11). The three major groups of muscular proteins can be myofibrillar, sarcoplasmic, and connective tissue proteins. Myofibrillar proteins constitute 50–55% of total protein whereas 30–34% of the total muscular proteins are represented by sarcoplasmic proteins (12). Oleic acid is the major fatty acid present in meat, is highly predominant in neutral lipids and is prepared from stearic acid with the help of a lipogenic enzyme (i.e., stearoyl Co-A desaturase). The quality of meat products is known to be affected by their composition together with the cooking time and temperature (13). Meat is a heterogenous food group with its composition varying with the meat category. Red meats such as in beef, lamb, pork, and processed meat like burgers and sausages have a higher content of fat compared to chicken. Generally, red meats such as beef and dark-colored meat derived from chicken and turkey are a better source of iron than white meats.

Distinctive heat transmission media has been used for the cooking of meat which includes thermal and non-thermal cooking methods. Thermal treatment involves the application of heat first of all because considered the most effective way of eliminating microorganisms causing food-borne diseases (14), although often not in an adequate manner (15). However, humans have been cooking meat for hundreds of thousands of years to improve its digestibility, to modify the physicochemical profile of meat as well as to prepare foods by using varying levels of temperature that in turn depends upon the product being prepared (16). The most widely used methods are grilling, boiling, pan-frying, roasting, and deep-frying (17). The thermal processing led to an alteration in the structural conformation of protein apart from altering sensorial traits like appearance, flavor, texture, and chemical characteristics of the ingredients, affecting tenderization and toughening (18–20). Heterocyclic aromatic amines, which are known to be potentially rich mutagenic/carcinogenic agents, are formed during meat's thermal processing and incomplete combustion of constituent organic material (21). Goluch et al. (22) thoroughly investigated the effect of various types of thermal processing techniques viz a viz pan frying, water bath cooking, grilling, and oven convection roasting on the nutritional composition and energy of meat of goose breast. Out of all these techniques, oven convection roasting stood out in terms of lowest energy value and retention of the highest nutritional content with respect to fat and essential minerals such as phosphorus and sodium.

The novel non-thermal technology has certain advantages over conventional technologies including enhancing the product quality and safety while also having an advanced level of automation besides having more accurate control over the processing method (23), but the influence of non-thermal technology on the sensory quality of food can't be ignored (24). The safety and quality of cooked food could be improved by applying non-thermal technology conditioning prior to cooking. The novel heating technology for foods substitutes the conventional heating processes for providing thermal energy in cooking in addition to reducing cooking time, enriching quality factors, refining processing efficiency, and product safety. The prominent non-thermal processing techniques are highlighted by high hydrostatic pressure, UV-light, ultrasound, and pulsed electric fields that prove to be beneficial in ensuring the organoleptic as well as the nutritional constitution of food (23) (**Figure 1**).

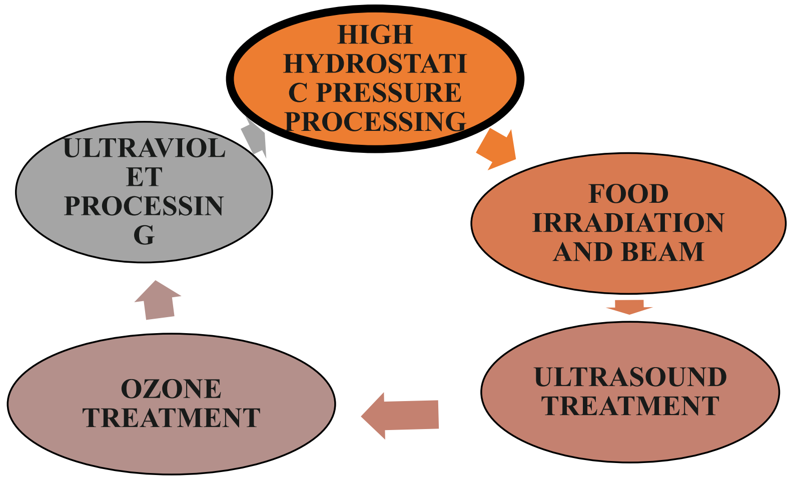

FIGURE 1
Different types of novel techniques used in meat processing.

It has been known for a long that processing at higher temperatures led to protein denaturation along with diminishing the water-holding capacity of meat (25) while structural deformations can be produced even at lower temperatures (26). When cooked at 58–64°C temperatures, the helical/crystalline structure of collagen molecules in meat shifts to a randomly coiled/amorphous one (27) which is accompanied by the bursting of hydrogen bonds resulting in the lowering of interaction between water and protein, relaxing of the structure of slender fiber along with tightening of the collagen structure. Unrestrained collagen fibers undergo shrinkage when subjected to a temperature treatment of 60–70°C (12), denaturation proceeding toward granulation, and increased solubilization followed by gelatinization due to the breakage of intermolecular bonds owing to an increase in heat (28, 29).

The high perishable rate of meat makes it highly imperative for its conservation by the following one or more processing techniques. In order to achieve this, various cooking methods used traditionally such as cooking in water and oven were put into practice since ancient times. Since these traditional methods have a few drawbacks such as a change in temperature between two locations within the meat, longer processing time, and reduced heating rate apart from a reduction in the overall quality of treated products. Amid this, various modernistic techniques have visualized evolution in recent years (30, 31). Commonly employed cooking methods such as boiling, roasting and grilling are accompanied by two methods of heat transfer. Heat transferred through the air in roasting or through water in sous-vide in a water bath involves a transfer by convection mode whereas in grilling meat is in direct contact with the heat source by conduction, which involves a comparatively shorter period of time for the cooking of meat (32).

With the increasing demand for high-quality foods, the application of non-thermal technologies has taken a spike in the food industry. The ultrasound treatments, high hydrostatic pressure processing, gamma and irradiation treatment are the most significantly implemented advanced industrial applications that have been potentially useful in inhibiting disease-producing microbes prevalent in meat and fish products (33). The aim of this review to measure the changes that occur in protein, sensory, chemical, and oxidative properties of meat during thermal and non-thermal processing techniques.

2. Thermal processing technologies

2.1. Roasting and grilling

Meat can be roasted by rotating it on a spit over a fire. Fat or oil is used as a basis because it is a dry heat technique. Direct grilling often exposes food to temperatures over 260°C. The Maillard reaction plays a critical role in the processing and cooking of foods, resulting in many chemical changes and being responsible for the generation of final colors and flavors (34). In a significant study, effects of grilling (230°C for 20 min) and roasting (190°C for 25 min) were analyzed on oxidation products of cholesterol in mutton and chicken using techniques such as saponification, extraction, derivatization followed by quantification by chromatographic analysis. Roasting treatment proved out to be much better as compared to grilling with respect to oxidation products of cholesterol. No significant difference was observed between raw mutton and raw chicken with respect to cholesterol with the former being more dominant than raw owing to high content of saturated fatty acids and cholesterol (35). Compared to other processing techniques, roasting increases lipid oxidation because it employs high temperatures for longer periods. Grilling, however, seems to have less impact on lipid oxidation than other cooking techniques (36).

This study aimed to elucidate the effects of cooking conditions on the physicochemical and sensory characteristics of dry- and wet-aged beef strip loins. Methods: Dry- and wet-aged beef aged for 28 days were cooked using different cooking methods (grilling or oven roasting) × cooking temperatures (150°C or 230°C), and their pH, 2-thiobarbituric acid reactive substances (TBARS), volatile compounds, and color were measured. Results: Cooking conditions did not affect pH; however, grilling resulted in lower TBARS but higher cooking doneness at the dry-aged beef surface compared to oven roasting. In descriptive sensory analysis, the roasted flavor of dry-aged beef was significantly stronger when grill-cooked compared to oven roasting. Dry-aged beef grill-cooked at 150°C presented a higher intensity of cheesy flavor, and that grilled at 230°C showed a greater intensity of roasted flavor compared to wet-aged beef at the same condition, respectively. Conclusion: Grilling may be effective for enhancing the unique flavor in dry-aged beef. In conclusion, the advantages of dry aging can be enhanced by grill cooking instead of oven roasting, as grilling improves desirable flavor and color. In addition, the grill-cooked dry aged beef might be appealing to consumers due to its intense roasted flavor, compared to grill-cooked wet-aged beef at the same cooking condition, and it is greater when cooking temperature is higher. Within the treatments in this study, grill cooking of dry-aged beef at a higher temperature (230°C) would be recommended (37).

Raw broiler charqui was subjecting to grilling, roasting, frying, and sous-vide techniques with sous-vide cooked samples exhibiting the lowest moisture loss than roasted and fried samples. High cooking temperature had significant effects on oxidation of proteins, tryptophan fluorescence, protein carbonylation, and disulfide bond formation of chicken charqui. Duration of cooking had a deep impact on free thiol groups, schiff base formation and hardness. Color of broiler charqui got affected adversely by the type of cooking technique which was attributed to Maillard reaction. In terms of quality, sous-vide technique proved out to be the most advantageous (38).

Chang et al. (39) assessed the impact of grilling and roasting on the concentration of seven polycyclic aromatic hydrocarbons, including chrysene, benzo(b)fluoranthene, benzo(k)fluoranthene, benzo(a)pyrene, dibenzo(a,h)anthracene, benzo(g,h,i)perylene, and indeno(1,2,3-c,d)pyrene in beef and pork meat, revealing that both grilling and roasting in beef and pig-induced polycyclic aromatic hydrocarbons. Roasting was evaluated to report the highest values of shear force for any type of meat measured by the Warner Blatzer test. While beef that had been boiled in a water bath displayed softness with shear force values that fell between roasted and grilled beef samples, meat that had been grilled and roasted showed substantial variations in tenderness.

It is important to understand the physical changes of meat texture during cooking, in fact, duration and temperature applied for cooking meat have a large effect on the physical properties of meat and eating quality (40). Moreover, tenderness is an important quality trait which determines satisfaction, repeat purchase and willingness-to-pay premium prices (41). Cooking is the final step prior to consumption and has a significant effect on sensory qualities (42). Heat-induced denaturation of major meat proteins, and actin and myosin denaturation have been associated with tougher meat, and collagen denaturation has been linked to a decrease in firmness (43). Heating temperature and rate also affect the extent of collagen denaturation, reporting that the temperature at which collagen denatured increased with the increased rate (44). Changes in these proteins are continuous with increasing temperature and, on the other hand, the level of tenderness fluctuates along the course of cooking, thus, protein conformational change alone cannot fully explain the tenderness of cooked meat (45).

2.2. Deep-frying

Being predominantly rich in water, lipids, proteins, vital amino acids, and several micronutrients including prominent minerals such as iron, magnesium, selenium, and zinc, meat is a crucial component of our diets. The majority of people take proteins as a key component of their diet (46). Deep-frying is a method of cooking that dates to centuries and has become widely patronized because of the uniqueness of its color and taste characteristics, becoming one of the most used cooking techniques also for meat (47). Deep-frying involves submerging food in heated oil or fat that has reached a high temperature, above the boiling point of water.

Different frying processes and their effects were studied on the nutritional, physicochemical and sensory profile of mackerel. Deep frying had significant adverse effects on lipid oxidation and protein degradation whereas overall acceptance score was incredibly increased by air frying. A reduction in perfluorinated compounds, few toxins, activity of trypsin inhibitor was exhibited during frying process apart from increase in the sensory parameters of mackerel. Lower rate of oxidation and retention of nutritional and sensory qualities of fried mackerel and minced mackerel products were reported in vacuum frying. An increase in volatile basic nitrogen and thiobarbituric acid reactive substances in mackerel was observed during frying. A huge impact was reported in the proximate composition as well as the mineral content of fried mackerel. The fatty acid profile of fried mackerel was also affected by the absorption of linoleic acid from oil, oxidative decomposition, and water loss. Amino acids were also decomposed by high temperature used in frying. This pivotal study concluded that frying process invariably influenced taste, color, and overall acceptance of mackerel (48).

Jin et al. (49) analyzed deep fat frying and hot air frying on texture, color difference, sensory score, and volatile flavor compounds of giant salamander meatballs prior to and after frying. Increased hardness, elasticity, and L* (brightness) whereas lower a*, b* value and fat content was reported in hot air-fried giant salamander meatballs. The relative content of aldehydes and ketones of fried giant salamander meatballs increased to a high extent. Sobowale et al. (50) investigated the effects of optimized cooking time (30, 45, 60 min), frying temperature (150, 170, 190°C) and time (3, 6, 9 min) on the moisture content, moisture loss, fat and protein content, color, textural, and sensory characteristics of deep fat fried goat meat sausage by using response surface methodology. The overall quality, texture, and sensory characteristics of goat meat sausage were significantly affected by the frying conditions. Nevertheless, the storage and microbiological studies of deep fat fried goat meat sausages need to be explored to a high extent. In comparison to other procedures, high temperature (frying) results in a greater loss of moisture. One of the most often used thermal techniques for chicken meatballs is deep frying. Additionally, various frying temperatures and periods were employed as research factors. The amount of heterocyclic aromatic amines created by this frying method is less than 1 ng/g. According to research, deeper frying at an elevated temperature for a prolonged period of time caused chicken meatballs to lose weight more quickly (46). The final protein digestibility of these foods depends on the ingredients added (i.e., meatballs contain flour), but however, some studies reported that the protein retention in meat after the deep-frying process ranged from 96 to 100% (47).

2.3. Steam cooking

The duration of steam cooking may vary from short duration of time (30–40 min) for small cuts of meat to longer durations for a whole leg of lamb (51). Notwithstanding the fact that the application of superheated steam in drying of food can render various avenues for research, there is still less reporting about its utilization in the preparation of quality meat products (52). Steam cooking is less time consuming and involves uniform distribution of heat (53). Quite similar to other processing techniques, steam cooking induces alterations in meat proteins *via* denaturation and protein aggregation affecting the digestibility of muscle proteins (54).

Rakotondramavo et al. (55) conducted steam cooking on cooked ham prepared from pork Longissimus dorsi up to core temperature of 65°C. The *in vitro* digestibility and the digestion rate after steam cooking was evaluated. The overall digestibility and rate of digestion of the meat proteins was enhanced in comparison to raw meat due to denaturation leading to exposure of the interior of the previously native molecules. In another significant study exhibiting the effect of superheated steam along with marination and smoking on meat, superheated steam treatment showed higher overall acceptance in quality in leg meat as well as breast meat viz. a viz. nutritional composition and wholesomeness during storage period despite microbial and chemical spoilage (56).

Abdulhameed et al. (57) applied kinetic modeling using superheated steam cooking to analyze the texture and color changes of chicken sausage for a time period of few minutes. A gradual reduction in texture was observed with increase in cooking time and the L* value (brightness or lightness) of meat decreased in a linear fashion with cooking time thus depicting a first-order kinetic model for texture parameters and L*-value of color for meat.

2.4. Pan-frying

A Teflon-coated pan with little oil or fat as the foundation is used for pan-frying to quickly cook meat. The pan should have adequate width to prevent the meat from becoming crowded while cooking. Overcrowding a small skillet with meat lowers the temperature and delays cooking. According to Liao et al. (58), the beef is cooked using this approach at 180°C for 5–10 min. As opposed to the other cooking procedures, boiling and pan-frying produced rabbit meat samples with considerably greater protein and fat contents and much lower moisture content. Differently, other authors reported that pork meat could be pan-fried with a temperature that ranges from 150 to 250°C, with great sensory profile consequences. It seems that by increasing the frying temperature, the intensity of the sensory fried and burnt attributes increased as the boiled and piggy notes decreased, reporting that at a lower temperature the aroma profile is correlated to lipid oxidation products, while ah higher ones it is correlated to Maillard reaction products (59). The amount of heterocyclic aromatic amines produced as a result of this method of frying ranges from 2 to 70 ng/g of cooked meat (28). When compared to other cooking procedures, samples undergoing boiling and pan-frying showed considerably higher total volatile base nitrogen values. The increased protein content achieved after thermal processing methods as compared to other cooking techniques may be the cause of the higher total volatile base nitrogen values found.

2.5. Sous-vide cooking

Although consumer taste for meat kinds, such as beef, hog and chicken, differs among nations, regions and people, the intake of meat derived from poultry has been continuously rising over the world since antiquity (60). The process known as sous-vide involves heating raw beef that has been vacuum-sealed in a water bath to a predetermined temperature (61). The method is often referred to as the "cook-in-bag" methodology. Sous-vide cooking uses temperatures typically between 50 and 85°C, which means that it needs more time to heat up than traditional cooking techniques. It is considered a novel way of cooking characterized by meat sealed in bag (often vacuum) and cooked in water bath with the aim to retain more moisture, flavor and natural state (62, 63), with no Maillard reaction products formation (54), conserving some superior technological characteristics such as oxidative stability (63). Moreover, the vacuum packaging is able to prevent losses of volatile compounds and moisture during cooking, giving a better sensory quality (64). It lessens the temperature gradient and lessens harm to vitamins and proteins that are sensitive to heat (65). Additionally, it minimizes cooking loss and maintains juiciness. Hardness and shear force values are dependent on cooking time and the relationship of time and temperature, chewiness and cohesiveness of meat are significantly affected by cooking time, temperature, and the interaction between the two factors (66). Some authors reported that the shear force declined when the cooking temperature increased from 50 to 65°C (61). In comparison to steam-cooked beef, sous-vide beef had a reduced percentage of polyunsaturated fatty acids, including n-3, but a similar n-6/n-3 ratio. In comparison to the control group, sous-vide samples subjected to cooking at 60°C (SV60) reported a decrease in pH value. Many modifications occurs to proteins during cooking (cross-linking, aggregation, oxidation, and changes in conformation) (32).

2.6. Microwave heating

It is a prominent thermal treatment encompassing low consumption of energy and shorter cooking time (67). It facilitates the sustainability and efficiency of industrial production process apart from preserving the nutritional profile of the product (68). Several physicochemical modifications in proteins occurring in thermal processing get manifested in the form of several quality parameters predominantly palatability, bioavailability, digestibility, and cooking efficiency (67). As compared to conventional techniques, innovative and advanced methods such as microwave and ohmic heating have proven to be causing lower denaturation of meat proteins at high heating rates (69). Microwave cooking converts electromagnetic energy into thermal energy and is employed to process several meat products such as bacon, meat balls, and patties (70). Microwave cooking induced an increase in textural hardness apart from increasing water holding capacity leading to a higher deterioration of myofibrillar and sarcoplasmic proteins (67).

Li et al. (71) reported significant levels of protein denaturation, rupturing of cell membranes, solubilization of connective tissue, and presence of large gaps between meat fibers and muscle bundles in yak meat. Less structural damage of muscles was found in meat samples treated with microwave cooking which was attributable attributed to the less duration of cooking time. Few disadvantages are also encountered during microwave cooking with respect to alterations in the quality attributes of the meat such as cooking defects and unacceptable structural properties (72). Dong et al. (73) reported the significant effect of microwave treatment on the secondary structures, *in vitro* protein digestibility and microstructural characteristics of shrimp proteins and concluded that the total soluble protein content and *in vitro* protein digestibility got significantly after undergoing microwave processing.

2.7. Ohmic heating

Several ohmic heating techniques that employ electrical current to heat food ingredients have been developed and patented for more than a century. However, the processing of foods with flowable liquid-particulates is the only commercial use. Ohmic cooking produced beef products that cooked more quickly used less energy, and were safer; ohmic heating generates heat volumetrically inside the material and can raise the temperature at a higher rate (74). This cooking method results in a firmer product, characterized by higher hardness and lower springier than that of the conventional method (75). Ohmic heating significantly decreased cooking loss and enhanced juiciness (17, 76, 77). Numerous studies have demonstrated that ohmic heating, either alone or in combination with traditional cooking techniques, may be utilized as a cooking process to produce beef products that are safer. In comparison to steam cooking, ohmically cooked beef exhibited a more invariably lighter and diminished red hue, a decrease in cooking loss, but a rougher texture. The content and physical characteristics of the food subjected to heating have a significant impact on the efficiency of ohmic heating. The formulation of meat products intended for ohmic heating requires an understanding of both meat and non-meat constituents due to their possible impact on ohmic heating. The inherent amounts of electrically conductive elements in raw meats are adequate to permit ohmic heating, but the composition of the additional additives can significantly change these levels. A small-scale ohmic heating cell was used to assess the values of various beef slices during ohmic heating (78). According to Shirsat et al. (79), adding lean to fat enhanced the conductivity overall. The heating of meat emulsions and meat batters has been accomplished using ohmic heating. While traditional beef had a cooking loss of 27%, ohmic low-temperature long-time-treated meat had the lowest cook loss (25.20%) (76). According to Zhang et al. (80), the shorter heating times may have reduced coagulating tendency of myofibrils and the gelating capacity of collagen, which would have reduced the ability of the ohmic heated samples for an efficient binding and entrapment of water within the cooked meat, explaining the lower water holding capacity of the ohmically cooked samples.

3. Non-thermal processing technologies

Nowadays, non-thermal processing techniques are being used for the purpose of food preservation. The most widely used non-thermal processing techniques are shown in **Table 1**.

3.1. Irradiation

High-energy gamma rays (60 Co and 137 Cs), X-rays, and accelerated electrons are the three ionizing radiation types that can be employed to irradiate food (81). The inactivation of microbes in food is more strongly impacted by changing the intensity of irradiation. Meat is also preserved using irradiation for a number of days. Inactivation of *L. monocytogenes*, *E. coli*, and *S. typhimurium* in ready-to-cook chicken under a storage period of 15 days when exposed to gamma radiation at intensities of 0, 1.5, 3, and 4.5 kGy produced outstanding results (82). Even after 15 days of storage, the chicken that was ready to eat still had pleasing sensory and textural qualities.

In addition to its potential role in extending shelf life by preventing food-borne illnesses and spoiling, irradiation technology is a desirable sterilizing technique due to consumer readiness to pay for processing for food safety. However, the use of irradiation, at higher doses, has been found to cause some unfavorable changes in food, especially in foods like meat, whose color and lipid content serves as the primary defining characteristics. Even a small change in color or lipid content may cause consumers to reject the product (83).

Irradiation alters food components, particularly the lipids and proteins in meat, although it can also preserve the original quality of meat (84). Fats begin to oxidize on their own when exposed to radiation, which produces rancid off-flavors. With increasing irradiation dose, the thiobarbituric acid reactive substances levels of pork patties packaged aerobically increased (85). Food irradiation doesn't present any unique nutritional issues. Irradiation dosages up to 10 kGy do not appreciably impact the calorific value of macronutrients treated with radiations in food (86).

The consumer assumption that food irradiation involves nuclear technology restricts the growth of irradiation technology applications in the food industry sector. For the advancement of this technology, it is crucial to change customer perceptions and persuade them to purchase irradiated food, as well as to construct safer and more reliable equipment and optimize treatments (80).

3.2. Ultrasound

Recently, meat and fish have benefited from the use of ultrasound. Because it doesn't generate waste and causes less harm to the environment and human health (87, 88), it is regarded as a green preservation technique. This process does not require chemical additives that can leach out into the water apart from less production of sewage (89).

Ultrasound is acoustic energy, moreover, it is a non-ionizing, non-invasive, and non-polluting form of mechanical energy (90), characterized by a great potential to control, improve, and accelerate processes without damaging the quality of food (87, 91).

Microorganisms may be rendered inactive by the ultrasound process, which can also alter the conformational structure of proteins, unfold the structure, and even splits the protein peptide chains through a process known as cavitation. This process produces cavitation bubbles that expand over several cycles before abruptly collapsing. This causes the cavitation zone to experience severe temperatures (over 5,000 K), high pressures (1,000 atm), high shear energy waves, free radical generation, and turbulence. Microorganisms are rendered inactive by the breakdown of microbial cells, while meat is rendered more tender by the breakdown of animal cells (92, 93). Furthermore, the cell damage improves the textural qualities without affecting the nutritional quality (94–96). The impact of ultrasound processing on actomyosin particle size was observed and was related to the protein dissociation during cavitation, which also resulted in the removal of aggregates and agglomerates.

High-intensity ultrasound processing has the power to disrupt cellular and subcellular components, and the cyclic oscillation of the acoustic pressure weakens cell membranes. Proteins, minerals and other components migrate because of tissue damage, which also accelerates enzyme activity. After receiving ultrasonic therapy, broiler breast muscle shear force values may be significantly reduced (86) by eliminating spoilage bacteria and improving product stability while in storage, the advantage of using ultrasound is that it extends shelf life. According to observations, the degradation of important quality indicators such as color and total phenolics, flavonoids, ascorbic acid and total antioxidant capacity as assessed by 2,2-diphenyl-1-picrylhydrazyl free radical scavenging activity is not significantly impacted by ultrasound processing (97). But ultrasound can also have detrimental impacts on food quality, such as the development of off-odors and the deterioration of substances associated with nutritional values.

3.3. Pulsating electric field

Using pulsating electric field technology, food can be preserved while also being shielded from the growth of pathogenic organisms. It allows for the inactivation of bacteria

TABLE 1 Summary of the application of various thermal and non-thermal processing techniques on various types of meat.

Treatment types	Types of meat involved	Key findings	References
Microwave processing	Shrimp proteins	Decrease in protein digestibility	(73)
	Beef filet	Absence of carcinogenic polyaromatic hydrocarbons in the samples subjected to steam and microwave preheating	(135)
	Rainbow trout protein	Increase in protein digestibility	(136)
	Chicken, beef, pork, kangaroo, trout, salmon, prawn, and oyster	Negligible effects on the digestibility of meat	(137)
	Chicken meat	Increase in water holding capacity (WHC) whereas a decrease in sarcoplasmic protein solubility was reported in thigh meat	(67)
Grilling	Corn, trout, beef, prawns, and pork	Polycyclic aromatic hydrocarbons (PAHs) emitted from thermal cooking were able to reach the vulnerable AL region of the lungs	(138)
	Beef satay	Fluoranthene concentration of total PAHs was found to be highest (132 ng/g) in beef satay	(139)
	Chicken proteins	Increase in protein digestibility	(140)
	Beef and salmon	Production of the high level of heterocyclic aromatic amines (HAs) and polycyclic aromatic hydrocarbons (PAHs) in grilled salmon sample	(141)
	Grilled beef, pork, chicken, turkey	Decrease in proteolytic action of pepsin during gastric digestion	(142)
	Whole muscles of Goose breast meat	Highest retention of minerals viz. Ca, Mg, Fe, Cu, and Mn	(8)
Stewing	Pork	Decrease in protein digestibility and large particle size	(143)
	Pork	Decrease in protein digestibility of stewed pork than the cooked pork	(144)
	Chicken proteins	Decrease in digestibility of muscle proteins after 3 h of stewing	(145)
	Beef proteins	Partial digestion of small peptides was reported after 30 min of stewing	(146)
Infra-red processing	Lean beef meatball, Turkey	Total polyaromatic hydrocarbons (PAHs) detected were below the prescribed EC limits	(147)
	Pork, Turkey Breast, and Corned Beef	High levels of aspartic acid, threonine, and serine levels	(148)
	Hamburger patties	Samples heated with far infra-red radiation suffer less cookout losses, giving a more desirable yield	(149)
	Biltong (dried and cured meat)	Enhancement of microbial quality and satisfactory tenderness	(150)
Sous-vide cooking	Beef	An increase in protein solubility and protein digestibility was reported	(151)
	Pork	Increase in protein digestibility	(143)
	Beef steaks	A decrease in the small molecular weight peptides was observed	(152)
	Beef proteins	Negligible effect on protein digestibility	(153)
Boiling	Beef frankfurters	Decrease in pH of meat during digestion	(154)
	Hairtail filets	Increase in protein digestibility	
	Beef	Increase in digestion by proteases (trypsin and pepsin)	(155)
	Pork	Increase in digestibility of actomyosin	(156)
	Beef	Enhanced digestibility of muscle proteins	(157)
	Beef stripes	The concentration of benzofluoranthene, benzopyrene, indenopyrene, and benzoperylene was reported as 0.01–5.11 µg/kg	(158)
Pan frying	Beef	The high content of heterocyclic aromatic amines in pan-fried meat	(159)
	Minced beef	The addition of carbohydrates reduced the amount of heterocyclic amines	(16)
	Longissimus dorsi of beef	Control pan-fried samples reported a better odor and higher overall quality than the beer- and wine-marinated pan-fried steaks	(160)
	Hairtail fish proteins	Increase in protein digestibility	(161)
	Rabbit proteins	Decrease in protein digestibility	(162)

(Continued)

TABLE 1 (Continued)

Treatment types	Types of meat involved	Key findings	References
Ultrasound	Beef	Aggregation of myosin	(163)
	Squid mantle	Increase in hydrophobicity	(164)
	Chicken myofibrils	Negligible modification in primary structure of proteins	(165)
	Protein isolate from duck liver	Negligible modification in primary structure of proteins	(166)
High pressure processing	Tropomyosin from shrimp	Increase in surface hydrophobicity with increase in pressure	(167)
	Myofibrillar proteins from pork	Dynamic structural changes in soluble proteins, actin, and myosin due to aggregation	(168)
	Bovine *longissimus dorsi* muscle meat	Significant changes in the visual appearance and texture, higher breakdown of the parent proteins with high pressure (600 MPa), significant changes in myofibrillar structure	(169)
	Breast meats from Chicken	Conversion of α-helix and β-sheet into random coil and β-turn.	(27)
	Trichiurus Haumela Surimi	Conversion of α-helix into a random coil	(170)

while preserving the natural color, taste and texture of uncooked food, as opposed to thermal treatment. The pulsating electric field method allows for the safe and effective increase of meat and meat products' safety. Since the process happens swiftly and the pulse duration ranges from micro to milliseconds, the entire inactivation of microorganisms does not result in the heating of the conserved product (98). While pulsating electric field's non-thermal nature guarantees the preservative parameter of high-quality meat and significant nutritional retention even at high temperatures, high temperatures, which are typically used as one of the principal food preservation methods, are to blame for the degradation of vitamins and bioactive components.

Given that the pulsating electric field works by exerting its effects on cellular changes and enhanced permeability of the cellular structure derived from electroporation, it is worthwhile to acknowledge its effect on significant nutrients viz. nutritional minerals such as iron, zinc, potassium and phosphorus, which have been reported for beef (99). The alteration of cellular structure may result in mineral loss either due to purging loss over time due to diffusion and lack of a physical obstruction due to pressure brought on by protein denaturation (100).

3.4. High-pressure processing

High-pressure processing is a non-thermal technology with several uses in the processing of meat, including tenderization and salt reduction. It is a method used to reduce the quality issues with low-fat meat products, and, more recently, is an innovative approach to increase digestibility. High-pressure processing also referred to as cold pasteurization of food pertains to that non-thermal treatment that is currently one of the most popular replacements for thermal food preservation techniques employed by the food industry. It is frequently used to treat meat and meat products, as the meat industry uses about 29% of all industrial high-pressure equipment (101).

High-pressure processing allows the extension of the shelf life along with preserving the raw materials' intrinsic nutritive values and organoleptic qualities (such as taste, smell, color, and texture) (102). Muscle protein denaturation is induced by high-pressure processing therapy, which also alters protein unfolding and refolding, changing the protein's structure and properties. When proteins are subjected to high-pressure processing, their denaturation patterns are unpredictable and depend on the amount of pressure used as well as the protein's source. As a result, pressure-induced changes in protein structure can alter how easily proteins are absorbed during gastrointestinal digestion. Studies have shown that high-pressure processing facilitates the protein digestibility of a variety of foods, including muscle foods. Fresh meat's usual characteristics, such as texture and notably color, can be significantly altered by high-pressure processing since it alters fresh meat's quality criteria (103). According to reports, high-pressure processing treatment causes electrostatic connections to break down and stimulates sulfhydryl-disulfide bond exchange processes, which causes protein dissociation and unfolding of its structure. Intermolecular and intramolecular interactions lead to refolding following the treatment, which preserves the protein structure. Muscle proteins exhibit physiochemical changes like denaturation, dissociation, solubilization, aggregation, and gelation when subjected to high pressures, which modify their characteristics. Pressure, temperature, pH, and ionic strength all have a significant impact on these variables (104). According to studies, high-pressure processing causes significantly alters the color of fresh meat, although alterations in cured meat products are tolerable and rely on the product's water content and water activity value (103). Although the processes underlying high-pressure processing-induced lipid oxidation is not completely understood, it has been proposed that high-pressure processing can facilitate lipid oxidation by making iron from hemoproteins more accessible and by causing membrane disruption (103). One of the most significant elements in the non-microbial deterioration of meat is oxidation (105). Lipid oxidation typically does not become apparent right away after high-pressure processing, but it can be noticed during chilled storage (106).

4. Changes in meat and meat products during various thermal and non-thermal processing techniques

Cooking temperature and duration impact the physical characteristics and eating quality of meat. The distinctive meat proteins are denatured during cooking, which is what causes the meat's textural profile to undergo several structural alterations. Cell membranes are destroyed, meat fibers shrink, myofibrillar and sarcoplasmic proteins aggregate and form gels, and connective tissue shrinks and solubilizes because of these processes. Thermal treatment can lead to unfavorable changes in meat quality, including nutritive value loss due to lipid oxidation and modifications in a few protein segments (**Table 2** and **Figure 2**).

Cooking techniques alter the physical and biochemical properties of the protein, carbohydrates, lipids, and other minor components of meat, which in turn affect yield, tenderness, juiciness, flavor, and palatability (107). The effects of five different cooking methods (boiling, steaming, grilling, microwaving, and superheated steaming) on proximate composition, pH, color, cooking loss, textural properties, and sensory characteristics of chicken steak were studied. Moisture content and lightness value (L^*-value) were higher in superheated steam cooked chicken steak in comparison to chicken steaks subjected to boiling, steaming, grilling, and microwaving cooking. Superheated steam samples exhibited better sensory characteristics, tenderness, juiciness, and overall acceptability score. Thus, the application of superheated steam in a preheated 250°C oven and 380°C steam for 5 min ensured better quality characteristics and sensory properties of chicken steak (52).

The formation of another protein network and the thermal modifications taking place in muscle proteins during heating directly affect the yield, texture, and overall quality of the final product. Meat that is thermally tender after cooking results in toughening based on the cooking conditions (108). The level of shrinkage is a pivotal factor for the consumers preference as various thermal processing techniques alter the meat's structure unfavorably, and more shrinkage is viewed as a sign of inferior quality (109). Low temperatures and longer time lead to an increase in shrinkage during thermal processing. The level of shrinkage is well augmented to increase with temperature, thereby leading to a huge water loss during cooking (12).

Amid these detrimental effects of thermal processing techniques on products, a wide array of non-thermal processing treatments for the inhibition of microbes have been developed to combat the global demand for nutritive and natural food items. Amongst non-thermal technologies, ultrasound, high-pressure processing, pulsed electric fields and pulsed light treatment stand out in immobilizing microorganisms at ambient temperatures. This preserves the food components from thermal degradation apart from maintaining the organoleptic and nutritional profile of the fresh-like food products (110).

Non-thermal processing encompasses all those processing techniques leading to the destruction of microorganisms along with preserving food from various harmful thermal effects and prolonging product shelf life by keeping intact their physical, nutritional, and sensory attributes. The inactivation of microorganisms can be achieved to variable degrees by high the application of processing technologies prominently hydrostatic pressure, pulsed electric fields, high-intensity ultrasound, ultraviolet light, pulsed light, ionizing radiation, and oscillating magnetic fields (111). Non-thermal processing is indeed one of those significant technologies which have been applied in the food sector for prolonging shelf life and preserving food integrity at reduced processing costs. Non-thermal technologies clearly assist the environment, whether by increasing the process' total energy effectiveness or utilizing fewer non-renewable resources.

4.1. Changes in sensory attributes

Traditional cooking methods employ the application of high temperatures contributing to the destruction of nutritional components, flavor and color, etc. to a considerable extent (112). The distinguished aroma and flavor characteristics of meat during cooking are acquired due to the complex interaction of precursors originating from the lean and fat components of meat resulting in the development of volatile flavor compounds imparting a typical meat flavor (113). The sous-vide method is one of those methods which provides higher microbiological safety in comparison to conventional cooking (114). It leads to enhancement of tenderness, higher retention of color, and flavor, and reduction in destruction of protein, lipid, and heat-sensitive compounds (51). Ohmic heating for ground beef samples under different voltage gradients does not significantly affect the color of the samples. Such beef samples reflect more homogeneity in color and are devoid of a cooked crust layer on their surface (77).

The color of cooked meat is considered as a major determinant of safety and wholesomeness. An unacceptable brown color on the inside is an indicator of properly cooked meat whereas a pink appearance is correlated with uncooked

TABLE 2 Changes during various thermal processing techniques in various types of meat.

Thermal processing techniques	Meat types	Processing condition (Time/temperature)	Changes during processing	References
Steaming	Sturgeon fish	37–100 for 4–20 min	The best profound flavor precursor was found at 12 min	(154)
Vacuum heating	Sturgeon fish	70°C for 30 min, 60°C for 15–30 min	Tenderness/juiciness	(164)
Steaming, boiling and air frying	Tilapia fish	Steaming (100°C for 5 min); Boiling (100°C for 5 min); Frying (200°C for 10 min)	Enhanced metabolites specifically arginine detected in the frying	(171)
Boiling, frying, and grilling	Bacon, chicken nuggets, tuna, chicken breast, beef	Boiling (90°C for 10 min); Grilling (150°C for 4–8 min); Frying (70°C for 10 min)	Highest N^{ε} -carboxymethyl-lysine (CML) (21.2 mg/kg) found in grilled tuna. Lowest N^{ε} -carboxymethyl-lysine (CML) (9.42 mg/kg) found in poached chicken	(172)
Boiling	Grass carp and catfish	100°C for 5, 10, 30 min	Negligible effects on the free advanced glycation end-products (AGEs) in fish muscle. Formation of protein-bound AGEs	(173)
Sterilization in an oil bath	Beef, pork, and chicken meat	121°C for 10 min	Insignificant effect on advanced glycation end-products (AGEs) in meat. 0.6- to 3.6 times increase in protein-bound AGEs	(174)
Sterilization and pasteurization	Pork meat	Sterilization (121°C for 30 min); Pasteurization (85°C for 4 h)	N^{ε} -carboxyethyl-lysine (CEL) generation detected in sterilization; N^{ε} -carboxymethyl-lysine (CML) formation in pasteurization	(30)
Microwave heating	Bovine supraspinatus muscle	900 W for 2.5–10 min	Increase in the darkening of meat samples	(175)
Ohmic heating	Pork meatball	Heating rate = 4.9°C/min, internal temperature (74°C); 72 V	Firmer uniform microstructure with bright colors	(176)
Infrared and microwave heating before freezing	Pork	Infrared (40°C, wavelength of 4–14 μm, power of 600 W for 90, 120, and 150 s.); Microwave (50, 100, and 150 W for 90 s)	Significant improvement in the quality of meat	(177)

ones (115). Color of meat is one of the significant parameters which is an indicator of the meat quality reflecting consumer's preference can give reliable information about eating quality. Due to high temperature employed in cooking, an increase in hue angle values of cooked samples was reported as compared to raw samples. A kinetic model was developed to describe the texture and color changes of chicken sausage subjected to superheated steam cooking at temperature ranging from 150 to 200°C for 2–6 min. Hardness, cohesiveness, gumminess, and chewiness apart from brightness (L*), a* (redness) were evaluated. A gradual reduction in texture and brightness (L*) was reported with increase in cooking times and temperatures (57).

4.2. Chemical changes induced during processing

The myofibrils comprise of a mesh of protein networks of several different proteins in mutual interaction with each other thereby leading to stable protein complexes and muscle structures. The denaturation of globular heads of the myosin molecule starts at 40°C with structural modifications visible in myosin sub fragments alongside complete denaturation taking place above 53°C (116). Myosin starts the denaturation process simultaneously with the changes observed with low field NMR accompanied by a reduction in water-protein interactions leading to shrinkage and increased cook loss during the preliminary stages of low-temperature long-time cooking (117, 118). During heating at temperatures (58–64°C), there is a sharp transition in the collagen molecule from the crystalline (helical) state to an amorphous (randomly coiled) (119) which is mainly attributed to the breakage of hydrogen bonds resulting in the reduction of water-protein interactions followed by loosening of the fibrillar structure and contraction of the collagen molecule. Thermal treatment at temperatures of 60–70°C led to shrinkage of unrestrained collagen fibers (12). The denaturation process paves the way for granulation and increased solubilization and gelatinization owing to the breakage of intermolecular bonds with the application of intense heat (120, 121). During frying, it is the simultaneous heat and mass transfer of oil and air which induces a number of chemical

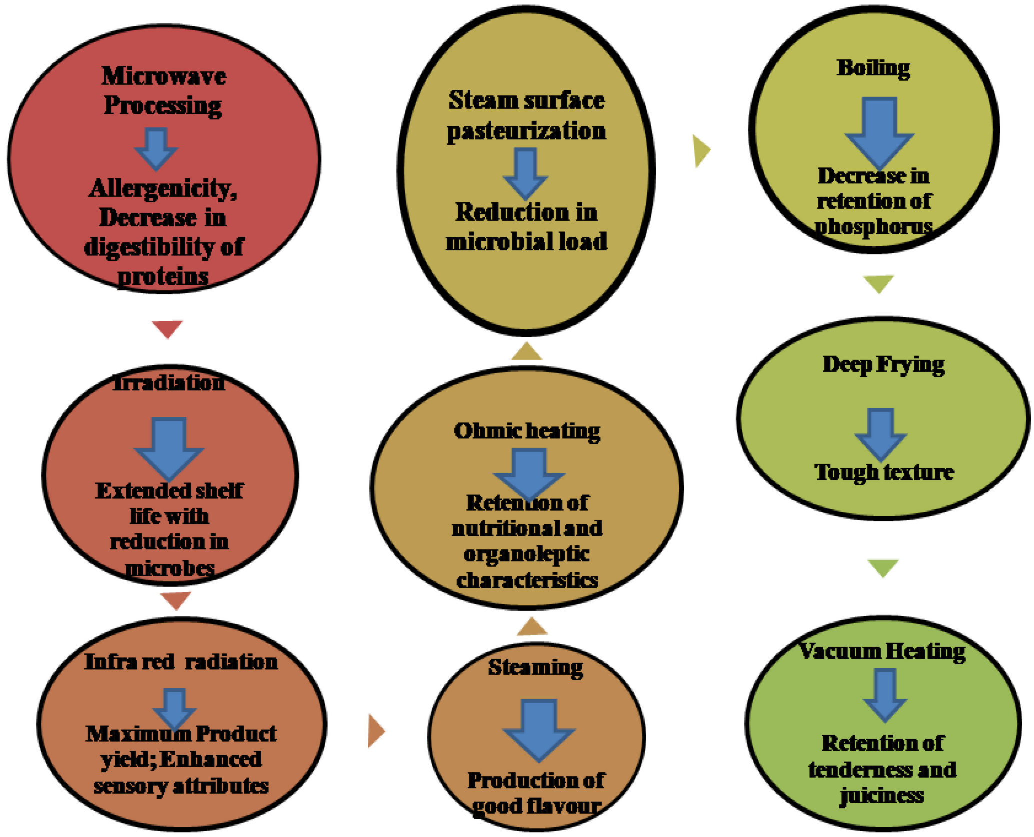

FIGURE 2
Various changes occur during meat processing.

changes viz. loss of moisture, formation of crust, uptake of oil, starch gelatinization, protein denaturation along with color changes induced by Maillard reactions and oil polymerization. Cooked meat acquires a characteristic texture by heat-induced changes in connective tissue, myofibrillar proteins and soluble proteins. The solubility of collagen molecules is dependent on the cross-linkage between collagen molecules within the connective tissue. These alterations in collagen solubility during thermal processing have a remarkable effect on the texture of poultry meat.

4.2.1. Oxidative changes

The great water activity of meat and fish products is a great breeding ground for the growth and activity of spoilage and pathogenic microorganisms (122, 123). Due to this, a high level of reduction of essential nutritive elements of these matrices such as proteins, amino acids and essential vitamins predominantly vitamin B complex takes place along with lipid degradation which is susceptible toward oxidative degradative phenomena (124, 125). These are the free radicals which are responsible for the acceleration of lipid oxidation as well as protein denaturation (90, 126). Lipid oxidation in meat during cooking imparts a characteristic taste and odor to the meat apart from inducing product deterioration, production of undesirable odors, rancidity, nutritional losses, and toxin production (127, 128). The typical aroma and flavor of meats as a result of cooking originates from volatile flavor components produced by thermally induced reactions during heating *via* four pathways such as the Maillard reaction involving the combination of amino acid or peptides with reducing sugars; lipid oxidation; interaction between Maillard reaction products with lipid-oxidized products and deterioration of vitamins (129). Thermal processing is one of the pivotal factors which results in moisture loss in meat and is quite substantial from a sensory point of view with a high moisture loss being an indicator of less juiciness of meat (130). Oxidative changes after thermal processing as shown in **Figure 3**.

4.3. Changes in meat protein during thermal or non-thermal processing

Manifold changes in the conformation in protein structure along with flavor, texture, and appearance, and the chemical properties take place during processing (**Table 3**). There are four different structures of proteins which have been identified

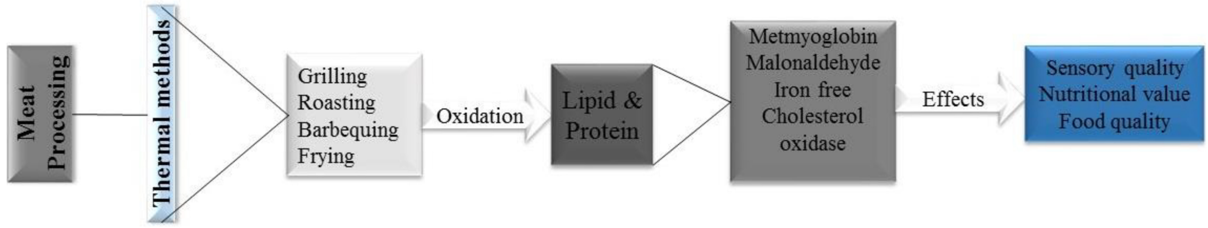

FIGURE 3
Oxidative changes after thermal processing.

TABLE 3 Effect of various thermal processing methods on protein derived from various meats.

Meat types	Thermal processing	Processing conditions (Temperature/Time)	Changes during processing	References
Shrimp (*Litopenaeus vannamei*)	Microwave processing	75–125°C for 5–15 min	Decrease in allergenicity and digestibility of proteins. Increase in antioxidant capacity	(73)
N-labeled bovine meat	Cooking in a steam oven	90°C for 30 min; 55°C for 5 min	Low digestibility	(178)
Frankfurters (beef, pork, and turkey)	Steam surface pasteurization	1140°C for 1.5 s	Retention of minerals, and vitamins. Reduction in microbial count on the meat surface	(179)
Lamb meat	Roasting, frying, pan-frying, or stewing	Roasting (200°C for 5–45 min); Frying (200°C for 2, 3.5, 5, 6.5, and 8 min); Pan frying (200°C for 2.0–8.0 min); Stewing (100°C for 1–6 h)	Higher heterocyclic aromatic amine content was detected in stewing	(180)
Lamb	Deep frying	180°C for 1–1.5 min	Desirable color and tough texture	(181)
Lamb	Smoking	Cooking (85°C for 30 min); Smoking (50°C for 20 min)	Reduction in heterocyclic aromatic amine	(182)
Frankfurter (beef + pork)	Smoking	Smoking (52°C for 10 min), Drying (56°C for 12 min)	Highest polycyclic aromatic hydrocarbons contents during smoking	(183)
Beef	Dry air and steam	The temperature of core (75, 85, 95°C)	Desirable tenderness and juiciness	(184)
Fresh beef and chicken breast	Boiling	10, 20, and 30 min	Greater nutritional peptides derivation and less retention of phosphorous	(185)
Pork	Grilling	200–260°C	Formation of heterocyclic aromatic amines and polycyclic aromatic hydrocarbons, retention of sensory properties	(186)
Skinless deboned chicken breast meat	Infra-red radiation and superheated steam	130–170°C	Maximum product yield, positive sensory attributes at 170°C	(187)
Minced beef	Irradiation	1–4 kGy	Extended shelf life with the reduction in microbial growth	(86)
Beef, pork, lamb, chicken, and turkey	Ohmic heating	3.5 kW, 15 A, 0–240 V, 50 Hz	Negligible structural, nutritional, or organoleptic alterations	(76)
Chicken patties	Steam-assisted hybrid oven	180–240°C	Reduction in the amount of carcinogenic compounds	(188)
Marinated lamb loins	Sous-vide cooking	60°C for 12 h	Minimized water loss and a firmer texture	(189)

viz. primary, secondary, tertiary, and quaternary. One of the most significant conformational changes prevalent in proteins upon the application of thermal treatment is the denaturation phenomena. During the heating process, the tertiary structure gets ruptured owing to external stress, predominately heat. Thermal processing also leads to the unfolding of the protein, rupturing of protein-protein association and finally leading to the destruction of collagen (12). Effect on protein structure after thermal processing as shown in **Figure 4**.

While heating between 40 and 60°C extending up to 90°C, aggregation of most sarcoplasmic proteins takes place. These heat-induced aggregated sarcoplasmic proteins can lead to the

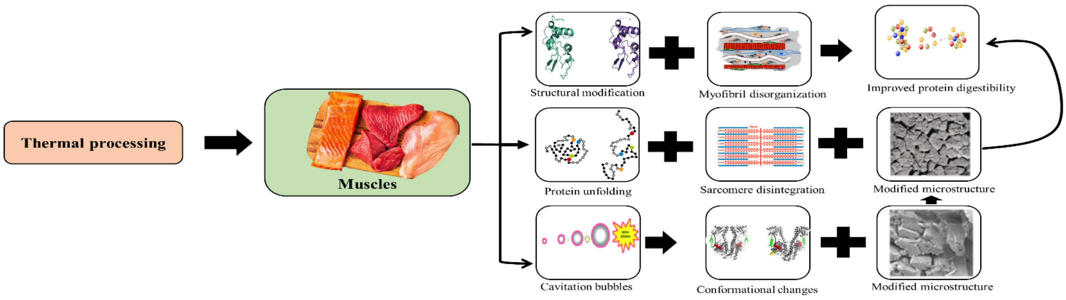

FIGURE 4
Effect on protein structure after thermal processing diagrammatically.

formation of gel within the constituents of the structure of meat resulting in the development of consistency in meat after cooking (131). Gel formation takes place with the denaturation of myofibrillar proteins in solution at a low concentration. This process commences with the rupturing of hydrogen bonds resulting in the opening up of the fibrillar structure followed by the contraction of the collagen molecule. When meat is heated at 60–80°C for 1-h, significant changes in the structure of proteins took place. Collagen in the epimysium remained unaffected after heating whereas the perimysial and the endomysial collagen attain granular structure at 60°C while the gelatinization process started at 80°C (46). A significant deviation was seen in the solubilization of collagen during the heating process. Thermal processing techniques such as cooking, roasting, grilling, frying, boiling, and sterilization have proven their potential in destroying pathogens but are accompanied by deteriorative effects on food composition and characteristics. The degree of denaturation in proteins during heating is dependent on the temperature and the protein under consideration resulting in the destruction of their quaternary and tertiary structures apart from the development of unfolded random shapes (132).

Different non-thermal processing technologies such as irradiation, ultrasound, cold plasma, pulsed electric field, and high-pressure treatments also tend to induce changes in the protein structure, solubility, and other functional properties (116). The primary structure of proteins is indicated by the amount and type of amino acids present in it. The formation of cross-links by disulfide bonds is the mechanism responsible for myosin aggregation. The ultrasound treatment has led to the cavitation phenomena formed due to free radicals by disulfide bonds (133). Few other findings have reported the significance of covalent and non-covalent bonds as the main interactions leading to the aggregation of muscle proteins subjected to ultrasound treatment. High levels of structural modifications were induced due to the destruction of bonds between amino acids and some distinct parts of proteins succeeded by protein aggregation followed by the degradation of inter-and intra-molecular hydrogen bonds in β-sheet and α-helix structures, respectively. This led to unfolding apart from the transition of a random structure into random coils and β-turns (134).

5. Conclusion

Textural properties of meat are an indication of several factors predominantly- animal, environmental, and managemental and processing ones. The protein structure of the meat is modified by phenomena such as denaturation, Maillard reaction or aggregation. Thermal processing techniques inclusive of commercial and domestic, modify the muscle proteins resulting in alterations in digestibility. Nevertheless, thermal processing of the meat ensures microbial safety to a considerable extent, it hampers the digestibility and bioavailability of nutrients during gastrointestinal digestion. Proper selection of operating conditions has noticable consequences not only on the meat quality but also on the efficiency of the cooking process. Improvement of the current cooking practices or investigating new cooking strategies is essential for the meat processing industry. Notwithstanding the fact that the traditional cooking techniques help in improving the appearance and taste of the lamb meat, these traditional methods such as grilling, smoking, roasting, etc. also pose several constraints in ensuring consumer health. The evaluation of the optimum cooking process for ensuring high quality and energy-efficient meat cooking aid the consumer to select an efficient cooking method and processing parameter of meat cooking. Inhibition of lipid oxidation in meat and meat products is quite imperative to the food industry for retaining the sensory and nutritional profile of meat and meat products. Novel processing techniques primarily microwave cooking involves the reduction in the energy requirement leading to less cooking losses. Apart from microwave cooking, it is infrared grilling and ohmic heating which can help to mitigate toxic compounds thus improving the sensory quality and ensuring the microbial safety of meat. Non-thermal treatments such as microencapsulation, high-pressure processing, and pulsed electric fields, irradiation have now become the most focused areas of research in the food sector in light of consumer cravings for nutritious, wholesome, and microbial-free food.

Author contributions

WK, JK, and MSA: conceptualization. MFA, NA, and MSA: methodology. PM and WK: software. WK, JK, SK, MSA, AM, and PD: validation, investigation, and data curation. WK, JK, SK, MSA, and PD: formal analysis. WK, JK, SK, K-u-WZ, MSA, AM, and PD: resources. AM, WK, K-u-WZ, SK, and JK: writing—original draft preparation. WK, SK, AM, and PD: writing—review and editing and supervision. WK, JK, SK, AM, and PD: visualization. WK, SK, and PD: project administration and funding acquisition. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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