Enhancing the quality of animal meat products by combining plant-based marinations and thermal processes: a treatise

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Abstract

Nowadays, natural preservatives, specifically involving marinades, are being applied to meat products to enhance various quality attributes. The need for food preservation has continually strengthened the processing of meat products. Besides the global production of bovine, porcine, ovine, and caprine animals, including poultry, that varies across continents, meeting the demands/needs of ever-increasing (global) population remains the focus. The growing consumer health awareness alongside intensifying global competition by meat producers cumulatively strengthens the call for healthier products, including preservation strategies. However, as published experimental/synthesized literature involving animal meat products, plant-based marination, and thermal processes continues to grow, there is a need to supplement existing information. Therefore, this treatise aims to discuss how the quality of animal meat products has been enhanced through plant-based marinations and thermal processes, drawing from plant-based marination: some key examples and usefulness; marination/marinades: briefs on preparation and applications; major thermal processes applied to marinated meat products; as well as quality implications of thermally processed marinated meat products. In certain instances, either marination would aid heat processing or vice versa, while in others, thermal processing may well be detrimental to marination.

Keywords: animal meat product; marination; herbs/spices; thermal treatment; product development.

Practical Application: The addition of marinades (the marination process) is capable of enhancing the quality of meat products. The application of thermal processes in some instances may strengthen the efficacy of marinades.

1 INTRODUCTION

Generally, meat products involve edible flesh/muscle tissues from certain domestic animals that serve as food, ranging from bovine, porcine, ovine, and caprine animals to poultry (domestic and non-domestic birds, excluding ratites), etc. (Cobos & Díaz, 2015). Globally, meat production would corroborate with the decreasing trend in all domestic animal species, which is believed to happen as animal farmers adapt to their self-consumption needs alongside limited market demands (Petroman et al., 2013). Typically, meat comprises approximately 72–75% water, 21% nitrogen-based compounds, 2.5–5% lipids, 1% non-nitrogenous compounds (vitamins), and carbohydrates, alongside about 1% ash (potassium, phosphorus, sodium, chlorine, magnesium, calcium, and iron) (Cobos & Díaz, 2015). The variation of meat composition depends on influences from several factors like animal species, breed, sex, feeding, muscle, etc. (Cobos & Díaz, 2015). Besides the global production of bovine, porcine, ovine, and caprine animals, including poultry, that varies across continents, meeting the demands/needs of the ever-increasing (global) population remains the focus. Meat/meat products remain a positive source of bioactive compounds for human health. The growing consumer health awareness alongside intensifying global competition by meat producers cumulatively pressures the need for healthier products, especially targeting preservation strategies (Pogorzelska-Nowicka et al., 2018). Indeed, food preservation continually helps strengthen the various meat processing strategies. Furthermore, the preservation technology involves not only categories I and II (heat treatment), but also categories III and IV (shelf stability), which aim to either reduce water activity (drying, salting) or have the combined effect of reducing both pH and water activity (fermented products) (Vandendriessche, 2008).

Prior to understanding the importance of thermal processes, especially when applied to marinated meat products, preservation needs of meat products still persist. In this, there are processing categories, which, according to Hui (2012), would involve key steps like slaughtering, raw product, heat treated, fully cooked but not shelf stable, not heat treated but shelf stable, heat treated and shelf stable, as well as thermally processed and shelf sterile. From these, meat
products that emerge can include cured/cooked-cured, fresh enhanced/comminuted/reformed, dried/dried fermented, as well as frozen types (Cobos & Díaz, 2015). Nowadays, natural preservatives specifically involving marinades are being applied to meat products to enhance various quality attributes (Cheok et al., 2011; Istrati et al., 2015; Sokolowicz et al., 2021). In addition to how different herbs/plants are applied via marination to serve their purpose, the manner in which meat samples take up marinade into their muscles depends on (meat) type, (marination) technique, and the duration of (marination) process (Okpala et al., 2022; Siroli et al., 2020).

On the contrary, the advances in thermal processing over the decades have helped enhance consumer edibility, decrease microbial proliferation, and enhance flavor/textures of meat products. Examples of thermal processing include aseptic processing, cook-chill, grilling, laser-based packaging, ohmic heating, sous-vide, etc. (Okpala et al., 2023; Schellekens & Martens, 1992; Viegas et al., 2012). The advent of hurdle technology, along with various conventional heat processing techniques and/or novel thermal processes, would be combined and applied to marinated meat products. However, as published experimental/synthesized literature involving animal meat products, plant-based marination, and thermal processes continues to grow, there is a need to supplement existing information. Therefore, this treatise aims to discuss how the quality of animal meat products has been enhanced through plant-based marinations and thermal processes, drawing from plant-based marination: some key examples and usefulness; marination/marinades: briefs on preparation and applications; major thermal processes applied to marinated meat products; as well as quality implications of thermally processed marinated meat products.

2 PLANT-BASED MARINATION: SOME EXAMPLES AND THEIR POTENTIALS

The use of extracts from fruits, herbs, and plants gains popularity given consumers’ desire for so-called “natural additives,” the latter of which refer to those naturally found with multiple attributed benefits (Balasundram et al., 2006; Lorenzo et al., 2018). As among very important alternatives to chemicals, plant sources remain increasingly applicable to meat products (Jayasena & Jo, 2013). Among several techniques being employed to increase the tenderness of meat, the marination approach appears very promising, especially in terms of its capacity to enhance flavor and water-holding capacity (Vişan et al., 2021). Specifically, marination refers to the process of treating meat with a variety of herbs, spices, organic acids, salt, and oil in order to tenderize and improve its flavor (Meneses & Teixeira, 2022). When combined with other preservation methods, marination makes common foodborne bacteria more vulnerable (Meneses & Teixeira, 2022). Indeed, the composition of marinades would directly influence the efficacy of the marination process; hence, considering the desired marinated product, either single or combined plants could be utilized. Previous studies of different plants/herbs employed for marination purposes are shown in Table 1. In addition to garlic (Allium sativum L.), ginger (Zingiber officinale), pineapple (Ananas comosus), and rosemary (Rosmarinus officinalis L.) (as shown in Table 1), several plants and herbs have shown potential as meat-marinating ingredients.

Garlic is one of the most often used culinary flavoring components (Gokoglu et al., 2012). Numerous studies have shown that garlic may lower the population of Streptococcus, Klebsiella, Proteus, Bacillus, Clostridium, E. coli, Salmonella, Staphylococcus, and Helicobacter pylori (Ankri & Mirelman, 1999; Banerjee & Sarkar, 2003; Chen et al., 2018; Phan et al., 2019; Sivam, 2001). Garlic contains phenolic compounds considered to draw significant attention as antioxidants (Awuchi & Okpala, 2022). Numerous scientists have used garlic-based marinades to enhance the quality and/or safety of meat products (Farhadian et al., 2012; Nurwanotoro et al., 2015; Tkacz et al., 2021). Ginger is a significant root spice that is extensively utilized in the meat industry and in the culinary arts (Awuchi & Okpala, 2022; He et al., 2015). Moreover, ginger extract would incorporate the action of proteolytic enzyme zingibain, which could soften tough meat through a tenderizing impact (Himori-Kondo et al., 2022; Kaewthong et al., 2021). In addition to tenderizing meat, Putra et al. (2019) showed ginger juice to reduce the flavor and lipid breakdown of refrigerated Saanen crossbred goat meat. Besides containing the proteolytic enzyme bromelain, pineapple is among the fruits employed in the marination of meat products (Golden & Smith-Marshall, 2012; Kaewthong et al., 2021). Pineapple extract showed antibacterial action against Staphylococcus aureus given by the bromelain molecule alongside phytochemical constituents, such as Vitamin C and flavonoid (Loon et al., 2018). Food processors may use pineapple extracts to boost the tenderness and customer acceptability of chicken meat (Abdel-Naeem et al., 2022). Marinating beef in pineapple puree could optimize tenderization and reduce cooking losses (Lawrence & Lawrence, 2021).

Rosemary extracts are widely used as natural antioxidants (Cadun et al., 2008). It has been reported that rosemary contains antioxidant compounds including rosmarinquinone, rosmariphenol, and carnosol that are up to four times as potent as butylated hydroxyanisole and equivalent to butylated hydroxytoluene (Martínez et al., 2019; Nakatani & Inatani, 1984). Among the main marinating components, the bioactive compounds in rosemary extracts may possess antibacterial properties (Fellenberg et al., 2020; Gazwi et al., 2020; Lee et al., 2020; Lëšnik et al., 2021; Rashidíadé Abandansarie et al., 2019; Shen et al., 2022). Other plants/herbs employed in marination, as shown in Table 1, include koruk, black pepper, garlic/onion, edible mushroom, red pepper, tomato, coriander, blackberry, pomegranate, rosehip and grape, as well as sweet basil (Fu et al., 2022; Gibis and Weiss, 2012; Kim et al., 2010; Patriani et al., 2021; Sengun et al., 2020, 2021; Testa et al., 2019; Vişan et al., 2021; Yu et al., 2023). Green tea, white tea, yellow tea, oolong tea, dark tea, and black tea, lemon grass, turmeric, curry leaf, torch, hibiscus, lemon, thyme, oregano, sage leaf, hop, licorice root, curcuma, clove bud, oregano leaf, and ajwain seed, as well as Bay leaf, have also been reported (Bilgin Fişiciler et al., 2018; Gibis and Weiss, 2010; Gokoglu et al., 2012; Mahrou et al., 2003; Rababah et al., 2011; Sepahpour et al., 2018; Tarvainen et al., 2015; Wang et al., 2018).
Table 1. Previous studies of different plants/herbs employed for marination purposes.

<table>
<thead>
<tr>
<th>Plants/herbs</th>
<th>Study aim</th>
<th>Key findings</th>
<th>Reference</th>
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</thead>
<tbody>
<tr>
<td>Koruk</td>
<td>To test the efficacy of koruk products (koruk juice and dried koruk pomace) as a marination agent against high and low inoculum dosages of <em>Escherichia coli</em>, <em>Listeria monocytogenes</em>, and <em>Salmonella typhimurium</em> inoculation on chicken flesh</td>
<td>Total acidity/phenolic content of marinating solutions made with koruk juice and dried koruk pomace, both boosted the efficacy of the marination process, which in turn increased the safety of poultry meat</td>
<td>(Sengun et al., 2020)</td>
</tr>
<tr>
<td>Grape seed and rosemary extract</td>
<td>To assess the effectiveness of water-in-oil marinades with grape seed extract or oil marinades including rosemary extract to minimize heterocyclic amines (HCAs) accumulation in beef patties</td>
<td>Rosemary and grape seed extract dispersed in sunflower oil or a water-in-oil emulsion inhibited the formation of various HCAs</td>
<td>(Gibis &amp; Weiss, 2012)</td>
</tr>
<tr>
<td>Black pepper, rosemary, oregano, thyme, basil, and ginger</td>
<td>To examine the nutritional, textual, and sensory effects of herbs and oils on Black Angus beef sirloin meat</td>
<td>Aromatic herbs and cold-pressed oils improved the beef’s aroma, taste, and texture (particularly tenderness and juiciness) after prolonged marination. Each aromatic plant and oil had a distinct polyphenolic profile</td>
<td>(Vişan et al., 2021)</td>
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<tr>
<td>Garlic and onion</td>
<td>To assess the antioxidant and meat quality impacts of garlic and onion juices marinated at 3 or 6% for cold-storing fresh pork</td>
<td>The antioxidant activity of juices (garlic and onion) on fresh pork during storage depends on marinade concentration. All treated samples obtained greater scores for taste, juiciness, and tenderness than untreated samples</td>
<td>(Kim et al., 2010)</td>
</tr>
<tr>
<td>Ginger and pineapple</td>
<td>To enhance the flavor of barbecued culled dairy goat using ginger and pineapple juices as well as sodium bicarbonate (SB)</td>
<td>Marinating dairy goat meat in pineapple juice and SB may result in a quality improvement</td>
<td>(Kaewthong et al., 2021)</td>
</tr>
<tr>
<td>Australian garlic</td>
<td>To determine the phytochemical properties and antimicrobial activity of Australian garlic cultivars (<em>Allium sativum</em> L.)</td>
<td>Observed significant bioactive phytochemical variations among garlic cultivars and tissues (skin and cloves). Australian garlic skin and cloves contained more bioactive phytochemicals than imported commercial garlic</td>
<td>(Phan et al., 2019)</td>
</tr>
<tr>
<td>Edible mushroom</td>
<td>To evaluate qualitative characteristics, microstructure, and protein degradation of pork longissimus dorsi marinated with edible mushroom powders</td>
<td>Mushroom-based marinade enhanced the water holding capacity and tenderness of pork samples and minimized both Z-disk and M-line of pork sarcomere marinated with edible mushrooms</td>
<td>(Fu et al., 2022)</td>
</tr>
<tr>
<td>Sweet basil</td>
<td>To identify the physical quality of local chicken through marination with sweet basil seasoning</td>
<td>Sweet basil may decrease the pH value, retain the water content, minimize cooking loss and drip loss, and promote meat tenderness</td>
<td>(Patriani et al., 2021)</td>
</tr>
<tr>
<td>Garlic, pepper, onion red pepper, and tomato</td>
<td>To examine the effects of numerous commercial marinades and sous-vide cooking on the color, tenderness, cooking loss, and flavor of semi-membranous cow muscles</td>
<td>Sous-vide beef’s eating quality, including tenderness, as enhanced by marinades containing red pepper, garlic, pepper, onion, and tomato</td>
<td>(Tkacz et al., 2021)</td>
</tr>
<tr>
<td>Coriander</td>
<td>To examine the impact of coriander root and leaf extract marinades on the development and prevention of polycyclic aromatic hydrocarbons (PAHs) in roasted duck wing</td>
<td>Coriander root extract marinade inhibited the production of PAHs in roasted duck wings to a larger extent than coriander leaf extract marinade</td>
<td>(Yu et al., 2023)</td>
</tr>
<tr>
<td>Blackberry, pomegranate, rosehip and grape</td>
<td>To assess the impact of the marination procedure using fruit vinegar marination liquids on the quality and safety of meat</td>
<td>The most efficacious marinade for preventing pathogens was rosehip vinegar. <em>L. monocytogenes</em> was the pathogen most sensitive to marinating solutions, and rosehip vinegar effectively reduced the hardness of meat samples</td>
<td>(Sengun et al., 2021)</td>
</tr>
<tr>
<td>Olive leaf</td>
<td>To explore the efficacy of olive leaf extract against a broad spectrum of food spoilage microorganisms and the usage of olive leaf extract as a preservative in the anchovy fillet marination process</td>
<td>Because the extract extends the shelf life of the product without changing its organoleptic properties, it might be used in the food sector as a natural antioxidant and antibacterial food additive</td>
<td>(Testa et al., 2019)</td>
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</table>
Table 1. Continuation.

<table>
<thead>
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<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ginger, lemon grass, Turmeric, curry leaf, and</td>
<td>To examine the ability of four herbs and spices to prevent the development of HCAs in grilled meat</td>
<td>All spices/herbs, whether used alone or in combination, were observed to lower total HCA concentrations in marinated grilled beef</td>
<td>(Sepahpour et al., 2018)</td>
</tr>
<tr>
<td>dark and black tea</td>
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<tr>
<td>Green tea, white tea, yellow tea, oolong tea,</td>
<td>To examine the prevalence of PAHs in charcoal-grilled chicken wings and the effect of six tea marinades and their fundamental components on the formation of PAHs</td>
<td>The most effective inhibitor of PAH formation was green tea</td>
<td>(Wang et al., 2018)</td>
</tr>
<tr>
<td>dark tea, and black tea</td>
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<tr>
<td>Lemon, thyme, and rosemary</td>
<td>To determine how the microbiological profile and sensory quality of fresh chicken are affected by marinating the chicken in natural plant extracts prior to irradiation</td>
<td>Irradiation had an additional impact, along with the marinade's effect, in lowering microbial proliferation during storage</td>
<td>(Mahrou et al., 2003)</td>
</tr>
<tr>
<td>Tomato and garlic</td>
<td>To examine the impact that extracts of tomato and garlic have on preventing the oxidation of lipids in anchoyces that have been marinated</td>
<td>Both tomato and garlic extracts showed inhibitory impact on the lipid oxidation of marinated samples. However, tomato extract seemed more efficient over garlic extract in preventing lipid oxidation</td>
<td>(Gokoglu et al., 2012)</td>
</tr>
<tr>
<td>Grape seed and green tea</td>
<td>To examine the effect of natural extracts of green tea or commercial grape seed in combination with different concentrations of synthetic tert-methyl-butyldihydroquinone on lipid oxidation and the redness of goat meats</td>
<td>Plant extracts would substantially reduce lipid oxidation in goat meats, although grape seed extract enhanced redness, although green tea extract lowered it</td>
<td>(Rababah et al., 2011)</td>
</tr>
<tr>
<td>Bay leaf and green tea</td>
<td>To analyze the microbiological, sensorial, and physical aspects of bay leaf and green tea extract marinades on anchovy</td>
<td>Green tea and bay leaf extracts lowered the microbial load, TVB-N concentration, and TBARS (thiobarbituric acid reactive substance) level, despite the undesirable dark color it produced</td>
<td>(Bilgin Fıçıcılar et al., 2018)</td>
</tr>
<tr>
<td>Rosemary, oregano, sage leaf, hop, licorice root,</td>
<td>To investigate the impact of plant extracts high in carbon dioxide on the oxidation of triacylglycerol in Atlantic salmon during cooking and storage</td>
<td>Marination with plant extracts could increase the fish shelf life, alongside positive impact of variety of plants as marinade components</td>
<td>(Tarvainen et al., 2015)</td>
</tr>
<tr>
<td>curcuma, clove bud, oregano leaf, and ajwain seed</td>
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<tr>
<td>Hibiscus</td>
<td>To investigate the feasibility of preventing the formation of heterocyclic aromatic amines (HAAs) in fried beef patties by employing marinades with varying concentrations of hibiscus extract</td>
<td>Marinating meat using hibiscus extracts prior to frying may inhibit the formation of PhIP and MeIQx without negative impact to organoleptic characteristics</td>
<td>(Gibis &amp; Weiss, 2010)</td>
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</table>

3 MARINATION/MARINADES: BRIEFS ON PREPARATION AND APPLICATIONS

To reiterate, the purpose of marination of meat products has traditionally been to improve flavor/tenderness as well as enhance product shelf life. Marination importantly targets to increase raw meat yield, which could provide advantages to consumers/producers, especially in attaining a juicier meat texture alongside reduced water loss during cooking (Alvarado & McKee, 2007). Herbs/spices and water are the two primary functional components of plant-based marinades. Improving the appearance and quality of meat products with a range of flavors and aromas remains crucial when incorporating plants and herbs into marinade solutions. In addition, the antioxidant and antibacterial properties would vary with marinade compositions. To achieve this, extracting the precise concentrations from herbs and spices by adding water can be challenging. Furthermore, the addition of water prior to marination compensates for the anticipated weight loss during cooking, thereby maximizing product juiciness/yield (Xiong, 2005). Indeed, water acts as a carrier and dispersant for salt, phosphates, sugar, and water-soluble flavoring and coloring agents in the marinade (Zhang et al., 2022). When applied to the surface of meat in high concentrations, salt acts as a preservative by improving the flavor, increasing the amount of moisture that is retained, acting as a synergist with sodium tripolyphosphate to extract salt-soluble proteins, dehydrating the meat, and inhibiting the outgrowth of Clostridium botulinum (Keeton & Osburn, 2001).

Major preparation steps for making a marinade are shown in Figure 1. These preparation steps, from assembly/collection of the herbs/spices from the source through separation/sorting to the refrigerated storage, would vary depending on factors such as location, culture/traditions, the meat type to be marinated, availability of supporting ingredients/flavors, and the period of use. Huffstetter (2020) demonstrated that despite the availability of bottled marinades found in various stores, consumers can make their own. Capably, the enzymes in marinades help to break down fibers, tenderize meat, as well as add flavor to meat products. Largely, the marinating process could resemble...
Marinades, there is the culinary perspective that marinade ratios are necessary. Alongside, marinades are dependent on flavor profiles, which are guided by such key components like oils, chili peppers, condiments, wine, vinegar, dairy, fruits, and herbs/spices. Marinade times are also essential; from a culinary perspective, meats like beef and lamb could be as short as 2 h and as long as 24 h, whereas poultry chicken/turkey could also be as short as 2 h but as long as 6 h (The Culinary Pro, 2022).

Table 2 contains information on marinating techniques, mechanisms of action, benefits, and drawbacks. In the meat industry, there are a range of marinating techniques, including

<table>
<thead>
<tr>
<th>Methods</th>
<th>Mechanism of action</th>
<th>Merits</th>
<th>Demerits</th>
<th>References</th>
</tr>
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<tr>
<td>Immersion or soaking</td>
<td>Completely immersing the substrate in the marinade and enabling the liquid to permeate the meat through diffusion over a time period</td>
<td>Most affordable technique of marinating; no sophisticated equipment needed; suitable for home or small businesses</td>
<td>No uniformity in ingredient distribution, time-consuming, and a lower and slower marinade absorption rate</td>
<td>Yusop et al., 2010</td>
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<td>Injection</td>
<td>As the probes or needles are removed, the marinade is injected, distributing the marinade throughout the meat product</td>
<td>More relevant to the meat sector; better control over the marinating process by providing a precise amount of marinade solution, shorter time, and possibility to utilize the remaining marinade</td>
<td>Higher cooking losses, may create holes in the meat and allowing for leakage, a probable diminution in the meat's ability to retain water, and an increase in purging. Expensive equipment, not practical or desirable for tiny meat portions</td>
<td>Yusop et al., 2012</td>
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<td>Tumbling</td>
<td>Marinating poultry meat to provide a ready-to-cook, value-added product, which involves massaging and tumbling to bring about extraction of protein exudates, at either the food processing plant or the supermarket or butcher shop</td>
<td>Protein coagulates upon heating to improve binding properties. The extracted protein acts as a sealer, which facilitates the retention of moisture contained within the meat tissue</td>
<td>Increased initial equipment expenses, may tear fragments with poor size or utility, more aggressive to the muscle</td>
<td>Alvarado &amp; McKee, 2007</td>
</tr>
<tr>
<td>Injection/tumbling combination</td>
<td>Injection process followed by tumbling process</td>
<td>Delivers the highest level of overall product improvement and the highest throughput of completed products in the shortest length of time. Optimizes yields and weight gain while minimizing solution loss. Sensory quality improvement</td>
<td>Increased cost of equipment, increased manpower for product transfer and handling, can increase bacterial numbers</td>
<td>Oyetunji, 2009; Williams, 2012.</td>
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</table>
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2021; Tkacz et al., 2021, 2022), who combined marination with Tkacz et al., 2019; Hong et al., 2016; Karyotis et al., 2017; Lee et al., 2018). However, when combined with non-thermal processes like steaming, boiling, and braising produced meats were shown to enhance the balanced nutrients and reduce the carcinogens. Combining steam injection with air convection in the oven chamber can help increase the tenderness and decrease the cooking losses of meat muscle (Murphy et al., 2001). Besides superheated steam and hot smoking (Cho & Choi, 2021) and microwave heating and steaming (Jantaranikorn et al., 2023), the combined use of marinating and air-steaming processing techniques for chicken breast meats, which result in minimal cooking loss and tenderized flesh, appear promising (Barbanti & Pasquini, 2005) and potentially improve proximate composition. Moreover, the extra sensible heat that comes from superheated steam can help elevate the anticipated temperature to surpass the

4 SOME THERMAL PROCESSES APPLIED TO MARINATED MEAT PRODUCTS

4.1 Sous-vide

The cooking procedure is considered one of the ultimate factors in determining the final quality of meat products. An adequate choice of final thermal processing is crucial for beef tenderness, flavor, and juiciness, and it should be selected uniquely for each (Guzek et al., 2015; Liu et al., 2020). Sous-vide cooking involves subjecting raw materials with intermediate foods to controlled conditions involving specific temperature and time (the low-temperature long-time cooking method) within heat-stable vacuumized pouches (Schellekens & Martens, 1992). Meat would be cooked at temperatures ranging between 55 and 95°C for many hours or days, depending on its type, thickness, and connective tissue composition, and then rapidly cooled (Ayub & Ahmad, 2019; Baldwin, 2012; Ortuño et al., 2021).

Sous-vide preserves sensory quality, reduces lipid oxidation, extends shelf life, eliminates cooking losses, and increases the process yield by reducing material, labor, and storage expenses (Thathsarani et al., 2022). Sous-vide processing alone might not be sufficient to ensure the quality and safety of meat products for consumers. However, when combined with non-thermal processes like marination, the results of sous-vide cooking could further excel. This was proved by a number of workers (Haskaraca et al., 2019; Hong et al., 2016; Karyotis et al., 2017; Lee et al., 2021; Tkacz et al., 2021, 2022), who combined marination with sous-vide cooking to improve the quality and safety of different meat products. For instance, Haskaraca et al. (2019) proposed that marination with grapefruit seed extract in sous-vide-processed Doner Kebabs would increase the microbiological safety of these goods by inactivating Listeria monocytogenes, thereby protecting public health. The addition of the marinade boosted the pathogen's sensitivity to heat throughout this phase. Another instance is Karyotis et al. (2017), who demonstrated that sous-vide cooking effectively eliminated Listeria monocytogenes and Salmonella spp. from marinated chicken breast.

Sous-vide applied to chicken breast with lime juice (as a marinade) enhanced the meat quality by suppressing the pink discoloration and bacterial development (Hong et al., 2016).Probably, lime juice marinade might have contributed to preventing the pink coloration of cooked sous-vide chicken breasts by preserving their refrigerated freshness for up to 14 days. More so, the use of a marinating process prior to the application of sous-vide cooking could improve the flavor, tenderness, and juiciness of beef meat (Tkacz et al., 2021). Red pepper, garlic, onion, and tomato-based marinades facilitated beef steak production with promising quality attributes, such as high sensory scores as well as reduced shear force and cooking loss. Additionally, marinating would positively influence the fatty acid content of beef, thereby enhancing the production of ready-to-eat meat products (Tkacz et al., 2021).

4.2 Boiling/steam cooking

Steaming, air-steaming, and superheated steaming are steam-based cooking procedures commonly employed in the meat sector (Barbanti & Pasquini, 2005; Bowker et al., 2018; Cho & Choi, 2021; Choi et al., 2016; Modzelewska-Kapitula et al., 2019; Mudalal et al., 2014; O’Neill et al., 2019a). Steam cooking has been modified from the normal oven cooking process by injecting steam into the oven chamber to produce juicer meat products. Steam cooking occurs at a higher temperature than sous vide, ranging from 100 to 240°C (Isleroglu et al., 2015), wherein the meat is cooked to the necessary temperature within a certain time period (Modzelewska-Kapitula et al., 2019). Steam cooking marinated pork chops under high pressure, examined by O’Neill et al. (2019a), showed improved physicochemical (cook loss, moisture content, WBSF, and n-6:n-3 PUFA ratio) and sensory (texture, tenderness, juiciness, and OSA) attributes. Kougiakka et al. (2022) examined the qualitative attributes of boiled snail fillets marinated with acids, salt, different oils, and spices. The hardness of the cylindrical mid-posterior region of the boiled snail fillet signaled the presence of the flesh’s fat and carbohydrate contents.

Elsewhere, Jiao et al. (2020) analyzed the nutritional and safety characteristics of Hengshan goat leg meat, wherein processes like steaming, boiling, and braising produced meats were shown to enhance the balanced nutrients and reduce the carcinogens. Combining steam injection with air convection in the oven chamber can help increase the tenderness and decrease the cooking losses of meat muscle (Murphy et al., 2001). Besides superheated steam and hot smoking (Cho & Choi, 2021) and microwave heating and steaming (Jantaranikorn et al., 2023), the combined use of marinating and air-steaming processing techniques for chicken breast meats, which result in minimal cooking loss and tenderized flesh, appear promising (Barbanti & Pasquini, 2005) and potentially improve proximate composition. Moreover, the extra sensible heat that comes from superheated steam can help elevate the anticipated temperature to surpass the
saturation point at a given pressure (Cenkowski et al., 2007; Choi et al., 2016). Besides, several cooking techniques on marinated chicken steak were evaluated, and it was found that chicken steak cooked with superheated steam had enhanced textural features and reduced cooking loss, as well as a greater overall acceptance than other cooking methods.

4.3 Grilling

Grilling, whether charcoal or oven grill type, involves significant quantities of direct as well as radiant dry heat transferred by conduction (Ježek et al., 2020; Liao et al., 2010; Schröder, 2003), which, when applied to animal meat products, produce a considerable range of compounds that confer specific aroma, taste, and flavor (Bassam et al., 2022; Tkacz & Modzelewska-Kapitula, 2022). Like from a typical oven grill, such direct/radiant heat would produce relatively high temperatures capable of facilitating fat and juiciness loss (Beckett, 2012), as well as reducing the cooking time of any given meat slice (Ježek et al., 2020; Schröder, 2003). Largely, oven-grilling is considered healthier than the charcoal type and is increasingly of research interest, particularly for animal/meat food products (Okpala et al., 2022). Additionally, there is increasing evidence that the oven-grill approach appears to be increasingly employed across households in various parts of the globe, which suggests this facility is commercially and widely available. Hence, one would consider the application of oven grilling to animal meat products as recommendable (Okpala et al., 2023).

Previous studies on grilling marinated animal meat products have ranged from establishing the formation of heterocyclic amine carcinogens (Salmon et al., 1997), PAHs (Viegas et al., 2014), reduction of carcinogenic HAAs (Viegas et al., 2015), to effects on quality attributes like nutritional, physicochemical, microstructural, and organoleptic/sensory attributes (Komoltri & Pakdeechanuan, 2012; Okpala et al., 2022; Vidal et al., 2020). For instance, Viegas et al. (2015) investigated the effect of beer marinades on charcoal-grilled pork, specific to the formation of HAAs. These researchers showed beer marinades would mitigate the consumption impact of well-done grilled pork meat, thereby reducing the formation of cooking carcinogens. Moreover, Okpala et al. (2022) analyzed the antioxidant, organoleptic, and physicochemical changes in various marinated oven-grilled chicken breast meat samples. These workers showed that the oven-grilling method was capable of moderating the antioxidant, organoleptic, and physicochemical value ranges in the various marinated chicken breast meat samples. Recently, Okpala et al. (2023) equally applied the combination of marination and oven-grilling to pork neck meat. The results showed a wide range of quality attributes, from the physicochemical to sensorial standpoints.

4.4 Roasting and frying

During this cooking process of frying, there is a high temperature at normal air pressure and rapid heat transfer, which helps to make it efficient (Negara et al., 2021). Moreover, when considering frying, it can also improve the nutritional value, flavor, and sensory qualities of foods (Ziaifar et al., 2008). Arcanje et al. (2019) assessed the effect of wine marination on the degree of lipid and protein oxidation, volatile profile, and sensory qualities of roasted beef strip steaks. In general, wine-based marination had a positive impact on the sensory qualities of roasted beef, lowering lipid oxidation and rancidity and providing fragrant esters, alcohols, and lactones. Al-Dalali et al. (2022b) studied the impact of frozen storage on the volatile aldehydes, volatile alcohols, lipid oxidation, and fatty acid content of marinated roasted beef. Marination of beef enhanced the amount of fatty acids and thiobarbituric acid-reactive chemicals, while the roasting procedure primarily contributed to the formation of several volatile compounds.

Using chemical and sensory evaluations, Al-Dalali et al. (2022a) showed the marination would enable various plant recipes to influence the taste profile of roasted beef flesh. Various marinade formulas would improve the aroma profile of roasted beef, especially in (marinade) solution comprising water, 2% salt, 0.5% sugar, 0.5% soy sauce, and spices. In the manufacture of braised pigeon, Qian et al. (2021) showed marinating and frying were able to influence the taste of the flesh. By braising and frying, the amount and concentration of volatile compounds were significantly altered. In addition to some alkenes and alcohols detected in marinated pigeon flesh, the frying activity enabled the Maillard process and fat oxidation to increase the formation of essential meat taste compounds such as benzaldehyde, phenylacetaldehyde, octanal, nonanal, heptanal, e-2-octanaldehyde, and others.

4.5 Microwave and ohmic heating

Providing significant commercial potential in the food processing business (Guo et al., 2017), microwave utilizes a dielectric heating method alongside electromagnetic wave energy of between 0.3 and 300 GHz (Jiang et al., 2014). Food materials would absorb microwave energy, which would result in microwave attenuation (Xu et al., 2021). Indeed, the microwave concept has broad usage in the food sector, including cooking, pasteurization, drying, sterilizing, baking, etc. (Chandrasekaran et al., 2013). Recent studies have shown that microwaves can be combined with other processing methods and subsequently applied to marinated meat products (Jantaranikorn et al., 2023; Pankyamma et al., 2021; Wang et al., 2022). For instance, Wang et al. (2022) studied the flavor attributes of marinated pork belly cooked using conventional pan-heating, microwave heating, and microwave coupled with conduction heating. Microwave heating was shown to disrupt the integrity of the microstructure and increase cooking loss (50.33%) and sodium ion concentration (10.8 mg/g) by about 1.5 times that of microwave coupled with conduction heating. Also, microwave heating may expedite the breakdown of proteins and the thermal destruction of ribonucleotides, resulting in larger concentrations of free amino acids and nucleotides compared to conventional thermal heating. Pankyamma et al. (2021) investigated the effects of microwave power and drying techniques on the quality of tuna chunks marinated with salt, chili powder, turmeric powder, and pepper powder. The samples marinated and dried at 700 W displayed excellent rehydration capabilities and enhanced microbiological stability, although lipid oxidation was increased in the same samples.
Ohmic heating is a volume heating method that generates heat depending on the resistance of the material to the applied current (Zell et al., 2010). Also providing significant commercial potential in the food processing business, ohmic heating involves the conversion of dissipated electrical energy into heat that elevates the system's temperature, prompting considerable changes in food material components and microstructure, such as protein denaturation and water migration (Ángel-Rendón et al., 2020; Gavahian et al., 2019). Given its quick processing time, ohmic heating would inhibit lipid/protein oxidation (Kang et al., 2021). The efficiency of ohmic heating relies on the composition and physical features of the given food item, particularly its electrical conductivity (Varghese et al., 2014; Zell et al., 2009). By utilizing the benefits of ohmic heating, Kamonpatana and Sastry (2022) examined pretreatment methods aimed to both enhance and reduce the electrical conductivities of different solid particles, such as chicken chow mein ingredients. The electrical conductivity of chicken was most difficult to modify by blanching alone, necessitating marination in conductive fluids for the necessary durations. The impact of ohmic cooking on the water holding capacity, cooking loss, and color of marinated pork short shank was evaluated by Ángel-Rendón et al. (2019). Ohmic cooking of pork might have advantages in the culinary trade owing to the shorter cooking durations that can be used without substantially impacting essential parameters such as cooking loss, color, and water holding capacity.

4.6 High hydrostatic and ultrasound techniques

Alongside the marination process, the incorporation of supplemental strategies to assure quality and enhance marinade absorption would require the effective utilization of available procedures. Retention as well as uptake of marinade could improve by combining with other technologies such as ultrasound (Shi et al., 2020; Xiong et al., 2020) and high hydrostatic and hydrodynamic pressure (Bowker et al., 2010; O’Neill et al., 2019b), the latter probably effective in enhancing the marination process yield (Xu et al., 2019). By testing the effectiveness of high hydrostatic pressure in accelerating pork chop marinade absorption, O’Neill et al. (2019b) demonstrated that 400 MPa could improve marinade absorption and hence enhance flavor acceptance. Depending on the pressure level used, the high hydrostatic pressure application improved the pork chops’ shelf life; nevertheless, the texture was significantly impacted. Moreover, the marinade seemed to conceal the decolorization/whitening impact of high hydrostatic pressure on raw meat. The utilization of hydrodynamic pressure processing increased the assessment factors of the marinating process, as indicated by Bowker et al. (2010). The hydrodynamic pressure treatment of turkey breasts resulted in better textural qualities with no adverse impacts on muscle color or water retention. Additionally, hydrodynamic pressure treatment boosted marinade absorption, processing yield, and the tenderness of the final cooked product (Xiong et al., 2020). Besides, the major impact of ultrasound coupled with SB-assisted marination on chicken breast meat was the enhancement of meat tenderization, water holding capacity, and curing efficiency. Elsewhere, Shi et al. (2020) demonstrated that ultrasound coupled with a marination procedure (using potassium alginate) may tenderize aged chicken breast flesh. By evaluating the softness of cooked meats, these workers detected reduced shear force, which helped optimize the tenderness of aged chicken breast.

5 SOME QUALITY IMPLICATIONS OF THERMALLY PROCESSED MARINATED MEAT PRODUCTS

Typically, meat must be prepared before consumption. Thermal processes cause several positive effects on meat, including inactivation of anti-nutrient enzymes (Sobral et al., 2018), taste and flavor enhancement, microorganism destruction, shelf life extension, tenderness (Abdel-Naeem et al., 2021; Bognar, 1998), and improved digestibility (Rodriguez-Estrada et al., 1997; Sobral et al., 2018). However, they also produce some negative effects like aromatic polycyclic hydrocarbons (Onopiuk et al., 2021) and nutritional losses (Rodriguez-Estrada et al., 1997). HAAs and PAHs are potential and confirmed carcinogens (Pogorzelska-Nowicka et al., 2022). Cooking reduces the nutritional value of meat by destroying some vitamins and minerals, decreasing the meat's moisture content, denaturing muscle proteins, and altering the structure of myofibrillar and connective tissue (Abdel-Naeem et al., 2021). In addition, heating accelerates lipid oxidation, particularly for PUFA fats, which are abundant in rabbit meat (Lopes et al., 2015). The methods of thermal treatment, the cooking environment (dry or wet), cooking temperature, and cooking duration significantly affect the above-cited cooking changes (Combes et al., 2004). In this sense, red blood spots (RBS) may be caused by the insufficient denature of blood residues in blood arteries owing to inadequate heat transfer (Sturkie, 2012). Potentially, thermal processes may also affect the number of antioxidants originally present in marinated beef (Thomas et al., 2010).

5.1 Inhibitions of carcinogens

Both HAAs and PAHs are essential carcinogenic and poisonous substances that are mostly found in cooked protein-rich diets, particularly meat products (Hsu & Chen, 2020). Accordingly, plant-based marinades prior to cooking have been researched for their inhibiting effects (Bao et al., 2020; Gumus & Kizil, 2022; Khan et al., 2021, 2022; Macit & Kizil, 2022; Yu et al., 2023). For instance, Yu et al. (2023) examined the impact and principal constituents of coriander root and leaf extract marinades on the development and inhibition of PAHs in roasted duck wings. Coriander root extract was found to inhibit the development of PAHs in roasted duck wings more effectively than coriander leaf extract. Phenolic compounds in coriander marinades seemed most crucial in PAHs inhibition.

Khan et al. (2022) examined the impact of Za’atar marinades on the development of polar and non-polar HCAs in fried beef patties. The ideal marination durations seemed so when a decrease in HCA exposure happened, which provided healthier meat products as well as potential and novel food safety hazards. Production differences in HCAs seemed likely linked to natural antioxidants present in Za’atar, which boost oxidative activity and result in the reduction and/or synthesis of HCAs within the thermally processed meat. Bao et al.
Okpala et al. (2020) investigated the mechanism of black pepper’s effect on HAAs in tilapia fillets cooked at various temperatures. Black pepper, often employed to enhance food taste, might lend its use in preparing fish given the HAA limitations. The addition of 1.0% black pepper largely inhibited total HAAs in the fried fish fillets, thereby enhancing the quality/safety of fried aquatic muscle products. Moreover, olive leaf extract marinades (Macit & Kizil, 2022) and Vaccinium myrtillus L. extract marinades (Gumus & Kizil, 2022) possess significant inhibitory capacity on the formation of HAAs in pan-cooked salmon and chicken thigh meat, respectively.

5.2 Red blood spots

Consumers as well as relevant stakeholders in the animal meat industry consider the occurrence of RBS to be rare/unacceptable in commercially prepared food. This is largely because it indicates undercooked meat products (Bae et al., 2018; Smith & Northcutt, 2003). RBS is said to occur when a red blood spot is detected inside/within transverse meat cuts. The most likely cause of this defect is when blood lingres within the vessels post-slaughter. The ingredients employed in marinade solutions may alter the thermal denaturation of hemoglobin (Hb), hence influencing the color of blood residues in vessels after cooking (Jantaranikorn & Yongsawatdigul, 2020). Furthermore, to prevent apparition of RBS, marinated chicken breasts have to be cooked to an internal temperature of 85°C for at least 1 min (Jantaranikorn & Yongsawatdigul, 2020). Moreover, the potential reduction of RBS in cooked marinated chicken breasts can occur using a combination of microwave heating and steaming (Jantaranikorn et al., 2023). Accordingly, microwave pre-heating for 7 min, followed by steaming to a core temperature of 82°C, seems an effective heating technique for lowering RBS incidence, along with reasonable cooking loss. Consequently, heat processes may decrease RBS during the marination.

5.3 Loss of nutrients

Thermal processes may affect the nutritional composition of meat and fish, including water content, lipid profile, amino acids, and bioactive components such as vitamins and polyphenols, therefore impacting the quality of the final product (Ersoy & Özeren, 2009; Garcia-Segovia et al., 2007; Jensen et al., 2014). Preventing nutrient loss should be a target, and that appears to be a promising takeaway that the use of marinades/marination process provides when applied to meat products prior to thermal treatment. For instance, Xie et al. (2022b) studied the effects of tea polyphenol treatments (control, unmarinated, and marinated) on the lipid oxidation of scallop adductor muscle during hot air drying. Marinating scallops in tea polyphenols enhanced the antioxidant activity, prevented lipid oxidation, and preserved the scallops’ nutritional content throughout drying. Another instance is the work of Xie et al. (2022a), which showed that marination with bamboo leaves might suppress lipoxygenase activity and interfere with free radical chain reaction. Moreover, Okpala et al. (2022) analyzed the antioxidant, organoleptic, and physicochemical changes in various marinated oven-grilled chicken breast meat. The oven-grilling method, by moderating the antioxidant, organoleptic, and physicochemical value ranges in the various marinated chicken breast meat samples, may well be controlling the loss of nutrients.

6 CONCLUDING REMARKS

This current treatise has provided relevant information about how the quality of animal meat products would be enhanced through a combination of plant-based marinations and thermal processes. Indeed, marination demonstrates great promise to increase the tenderness of meat as well as enhance its flavor and water-holding capacity. Moreover, the intention of novel thermal processing technologies remains to fulfill the expectations of customers, but only to a certain degree. From this synthesis, the addition of marinades (the marination process) was shown as a key to enhance the quality of meat products. Promisingly, the application of thermal processes would go further to strengthen the marinades’ efficacy. The direction of future work could be further literature synthesis involving systematic or meta-analysis of animal meat products that have been subjected to a combination of marinades/marination with thermal processing. Conducting such systematic or meta-analysis would help reveal new understanding of the existing data, especially the effectiveness and efficacy of the combination of marinades/marination and thermal processing.

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