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Review

Effect of Processing on Volatile Organic Compounds Formation of Meat—Review

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Abstract: Meat is a rich source of different volatile compounds. The final flavor of meat products depends on the raw material and processing parameters. Changes that occur in meat include pyrolysis of peptides and amino acids, degradation of sugar and ribonucleotides, Maillard's and Strecker's reactions, lipid oxidation, degradation of thiamine and fats, as well as microbial metabolism. A review of the volatile compounds' formation was carried out and divided into non-thermal and thermal processes. Modern and advanced solutions such as ultrasounds, pulsed electric field, cold plasma, ozone use, etc., were described. The article also concerns the important issue of determining Volatile Organic Compounds (VOCs) markers generated during heat treatment.

Keywords: volatile organic compounds (VOCs); meat flavor; thermal processing; non-thermal processing; cooking technique

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1. Introduction

The meat quality is considered in terms of the following characteristics: color, flavor, texture, tenderness, etc. [1–3]. It is considered that aroma is an important factor influencing customers' decision to purchase a meat product [4]. The main features of meat products depend on raw material (genetic conditions, breed, sex, feeding type, welfare, muscle's type, etc.), processing techniques (whole pieces, mincing degree, smoking process, etc.), and drying parameters (time, temperature, or humidity) [5,6]. These features lead to the formation of the typical meat and meat products flavor [7]. The VOCs which cause the characteristic aroma of cooked meat are obtained from reactions that occur during different processes. Some researchers found that precursors of aroma-effect compounds have a significant impact on the final flavor of cooked meat and on some of the volatile products of the flavor-creating reactions [7,8]. Meat flavor generated during heat treatment results from the interactions of precursors located in the raw meat. These actions contain pyrolysis of peptides and amino acids, degradation of ribonucleotides, and also sugar, Maillard reactions, Strecker degradation, lipid oxidation, degradation of thiamine and lipids, as well as microbial metabolism [9–11]. The Maillard reaction is significant due to the formation of a range of furanthiols and disultides that have a distinctive 'meaty' aroma and characterize very low odor thresholds [12].

The classes of organic compounds which are responsible for the formation of meat aroma are aldehydes, hydrocarbons, alcohols, esters, ketones, carboxylic acids, furans, ethers, pyrazines, pyridines, pyrroles, oxazoles and oxazolines, thiazoles and thiazolines, thiophenes, and other sulfur-containing compounds [13,14]. The origin of meat in combination with a specific cooking technique is one of the features which influences the perception of meat and final meat products quality [15].

Instrumental analysis is considered more practical for the detection of VOCs compared to sensory analysis. Gas chromatography (GC) is widely used to analyze and separate volatile aroma-contributing substances in meat [16]. Headspace solid-phase microextraction–gas chromatography–mass spectrometry (HS-SPME-GC-MS) and headspace–gas chromatography–ion mobility mass spectrometry (HS-GC-IMS) are more often used in liquid products [17]. GC-IMS is a new technique for hot gas phase separation detection [18]. Both methods allow us to describe the molecular level of a single volatile compound. An electronic nose based on ultrafast gas chromatography is a non-destructive and trustworthy method for VOCs analysis. This equipment has already been widely applied in both the field of quality control and science analysis [1,19–21].

Therefore, we decided to review the impact of various factors affecting the formation of VOCs in meat. Non-thermal and thermal aspects of VOCs formation were considered.

2. Genetic Parameters

Breed, Sex, Gender

Major factors altering meat's volatile profile are breed [22], sex, and rearing [23]. Moreover, factors such as diet [24], supplementation [25], castration, or age of the animal [26] can affect volatile substances content. Accordingly, the objective of many studies is to investigate the impact of these factors on meat VOCs. The main object of [22] was to evaluate the breed's impact on the quality of meat. Meat of goats (Alpine, Balkan, and Saanen) of the same age was analyzed. Determined parameters included chemical composition, composition of fatty acid (FA), and content of VOCs, among others. To analyze volatile compounds, the extraction procedure was conducted using gas chromatography–mass spectrometry (GCMS). GCMS-QP2010 Ultra with a SUPELCOWAX 10 Capillary GC column was used. A carrier gas was helium (flow rate of 1 mL/min). The injection temperature was 200 °C. The group of identified compounds were aldehydes, with hexanal being predominant among volatiles. The next identified groups were ketones, of which 2-butanone and 2,3-butanedione commonly occurred. No phenols and only low quantities of aromatic hydrocarbons and organic acids were present in the meat. The results showed that Balkan goat meat contained less VOCs than meat of other breeds. The fact that the content of aldehyde is determined by fatty acid and protein presence in meat indicated the impact of genotype and breed on the VOCs in meat. Besides that, ketones content correlates with the animals' diet, which led us to conclude that diet also influences the volatile profile. Among the different factors affecting meat flavor, one of the most important is the animal's diet, which is the main source of VOCs [27,28].

Liu et al. [25] research analyzed the impact of probiotics on lambs' meat quality including VOCs. Research was conducted with Sunit lambs. During the experiment, the animals were fed with control diet (CON) and 10 g probiotics/d supplemented diet (PRO). Detection of volatile compounds was conducted using the electronic nose device PEN. First, 3. 5 g of sample was placed in a vial and then incubated. The data were collected for 120 s (gas flow rate of 400 mL/min). GCMS was used for further evaluation of the volatile flavor compounds. The solid-phase microextraction (SPME) technique was used for extraction of volatile compounds. Fiber was exposed to each sample and, after absorption, was inserted into the injection port at 250 °C for 3 min for the GC analysis. The carrier gas used was helium, at a flow rate of 1 mL/min. VOCs were identified by comparison with the library standard database and located based on relative odor activity value (ROAV). VOCs with ROAV > 1 were located as the key flavor compound, whereas those with ROAV 0.1 to 1.0 were considered as a flavor modifiers. In the two groups, 31 VOCs were observed. Seven of them were affected by probiotics supplementation. The meat samples of the supplemented group were characterized by lower overall odor intensity compared with the CON group. The results indicated higher abundances of sulfur and nitrogen oxides in the CON samples, whereas higher contents of long-acyclic alkane were identified in PRO lambs' meat. It was claimed that addition of probiotic in an antioxidative capacity affects the volatile profile, which improves the lamb meat flavor.

The effect of diet on VOCs was studied by researchers [24]. The work focused on the differences between quality of light meat of goat reared with natural milk (NM) and with applied milk replacers (MR). The main ingredients of milk replacers were whey and skimmed milk. The meat of eight breeds reared on three farms was analyzed. GCMS was used to identify the VOCs in the cooked samples. First, 1 g of cooked and minced meat was weighted into a 5 mL headspace vial. The SPME technique was used for VOCs extraction. The SPME fiber was subjected to exposure to a vial headspace in a warm water bath with agitation. A Hewlett–Packard GC coupled with ion-trap mass spectrometer was used. Helium was used as a carrier gas. Furthermore, n-alkanes were run to calculate the Kovats indexes. Volatile substances including aldehydes, ketones, and hydrocarbons were identified. Interaction between breed and the rearing system had an influence on VOCs content. It was stated that the volatile profile of meat clearly depended on the breed, and that the rearing system had smaller impact on VOCs level.

The aim of the study [23] was the comparison of free-range (FR) and cage-range (CR) breeding on the flavor compound of two breeds of chickens. In the cage-range system, each chicken was kept in a single cage. The FR chickens were located in an indoor house and had free daytime access to a paddock. All animals were fed the same diet. No antibiotics or probiotics were used during the trial. The headspace SPME technique was applied for the extraction of VOCs. The SPME fiber was exposed to a vial containing the extract of the meat sample. GCMS 2010 Series system was used to analyze the VOCs. The results showed that the content of all VOCs, except acids, was higher in the FR group compared to the CR group. The most common group of VOCs was carbonyls. It was stated that meat flavor was associated with the different housing systems. The objective of the study [26] was the analysis of VOCs of lambs (2, 6, and 12 months of age). Eighteen female animals were used in the research. They were offered the same diet and water. For VOCs analysis, GC-IMS was used. After the sample incubation, the headspace gas was injected using splitless mode. Nitrogen was used as the carrier gas. For the external standard for retention index (RI) calculation, N-ketones from C4 to C9 were used. The VOCs were identified by comparing the RI and the drift time of the standard in the GC-IMS library. Forty-four VOCs were detected. Aldehydes, alcohols, and ketones were the most abundant groups of compounds. The main conclusion was that the age of the animal affects the VOCs profile of meat.

3. Non-Thermal Processing

3.1. Aging Process

Post slaughter meat aging has an effect on its tenderness [29], as well as improving the flavor [10]. Changes in meat are the effect of various biochemical and structural transformations of proteins [28,30]. The process of lipid oxidation occurs during chiller storage of meat [31]. Two different methods of beef aging can be distinguished: “wet aging” and “dry aging”. The “wet aging” method is used more often. It is characterized by the storage of vacuum-packed primal cuts at low temperature. The second method is “dry aging”, where meat is stored without packaging in controlled parameters [32]. The creation of specific flavor attributes is characteristic of “dry aging” [33,34].

3.2. Packging and Storage

Packaging and storage parameters may impact the quality of meat. Packaging systems such as active packaging [35,36], MAP and vacuum packaging [37] may provide alternatives to air-packed meat by improving their sensory quality. Another primary parameter which can compound the meat quality is storage time. The impact of prolonged storage time and different packaging methods was also examined in different studies [38,39].

Bhadury et al. [37] focused on the impact of different systems of packaging on the formation of VOCs in raw beef over time. Three packaged sirloin steaks with the same best before date were bought in a local supermarket. The packaging systems were MAP containing 80% O_2 and 20% CO_2, vacuum packaging, and cling-wrapped packaging. The SPME method was used for extraction of VOCs and GC coupled with accurate mass quadrupole time-of-flight mass spectrometry, with helium as the carrier gas used for volatiles analysis. Retention index and mass accuracy from libraries were used for identification. Thirty-five VOCs were identified. Three VOCs were common to all packaging systems and five were present in at least two packaging systems. This work showed that many compounds which were assumed to be generated by thermal processes are also obtained from a specific packaging system of raw beef without application of heat treatment. It was also stated that some of the VOCs which were detected in the research are meat spoilage indicators and give information about the freshness of packaged meat. The objective of the study [38] was to analyze the performance of hyperbaric storage (HS) to preserve meat at two different conditions for 60 days of storage. Raw pork in pieces and raw minced bovine meat was analyzed. The conditions used for HS were 60 MPa/10 °C and 75 MPa/25 °C. Refrigeration was used as the control method. HS-SPME was used for extraction and GCMS with helium as carrier gas was used for volatiles determination. Identification was based on a mass spectra database and individual standards. Seven aldehydes, six alcohols, and two ketones were present in both meat samples. Significant changes were observed throughout storage for volatile compounds. It was concluded that 60 MPa/10 °C hyperbaric storage up to 60 days characterized high potential for raw meat preservation, as it showed better preservation compared to refrigeration.

The objective of the research [39] was to compare the evaluation of VOCs in beef meat under vacuum and air packaging. Fresh beef tenderloin samples were stored for 11 and 21 days at 4 °C. Extraction was conducted using carboxen/polydimethylsiloxane fiber and, for analysis, GC coupled with a time-of-flight mass spectrometer was used. The volatiles were identified by comparing their mass spectra with those available in libraries. The results showed that VOCs in air-stored samples were more diverse compared with those in vacuum-packaged samples. The amount of volatile compounds in beef stored in air conditions gradually increased during the storage. The highest amounts were mostly produced between 9 and 11 days of storage. For vacuum packaging, the amount of VOCs remained stable, with the highest increase occurring between 11 and 21 days. It was stated that most of the identified volatiles were previously associated with beef spoilage. The results of this study indicated that some of the microbial volatile compounds' metabolites could be used as spoilage indicators, but further study is required in order to determine the permissible values of volatiles used as indicators.

In one study [36], active packaging with the use of olive leaf extract, high-pressure processing (HPP), and its combination was studied. The effect on volatiles of dry-cured meat during storage was evaluated. Four treatments were analyzed; all of them were vacuum packaged (VP). The control sample was only VP, and the other treatments were: active packaging with activity 17.5 mg TROLOX/cm^2, HPP at 600 MPa/10 °C and both of them combined. SPME was used for extraction, and GCMS with helium as carrier gas was used for analysis. Compounds identification was conducted via comparison of their linear retention indexes and mass spectra with those presented in libraries or with injected standards. In all samples, a total of 27 VOCs were identified, of which the most abundant were aldehydes, hydrocarbons, and alcohols. It was claimed that this sort of active packaging only caused slight changes in the VOCs in dry-cured meat and could not be used to prevent changes related to refrigerated storage.

Another study [35] examined active packaging based on rice bran extract. The control sample was only vacuum packed and the other treatments were active packaging, HPP, and a combination of both. The samples were stored at 4 and at 20 °C and analyzed on the 1st, 90th, and 180th day (only for 4 °C stored samples due to unacceptable changes in meat stored at 20 °C). As in the previous study, HSME and GCMS were used for analysis and linear retention indexes and mass spectra were used for identification. Thirty-eight identified compounds were found in all samples on the first day of storage, which indicates that none of them were derived from active packaging. The most abundant volatiles were aldehydes and alcohols. It was proven that active packaging based on rice bran extract had a noticeable effect on the VOCs profile of meat.

3.3. HPP

HPP is technology applied in food industry to extending the shelf life of products and obtain better safety. This process was examined by Pérez-Santaescolástica et al. [40,41].

The objective of [41] was to analyze the influence of HPP on dry-cured ham. Experimental samples treated with HPP at 600 MPa at 21 °C and control samples were evaluated. VOCs were extracted using the SPME method. One-hundred and sixteen compounds were detected in control and HPP-treated samples. The most abundant VOCs were alcohols, ketones, and aldehydes, but their contents in samples were affected by processing.

Another study [40] focused on the impact of HPP at different temperatures on VOCs of ham. HPP at temperatures of 0, 20, and 35 °C was investigated. Solid phase micro extraction method was used for VOCs analysis. SPME fiber was exposed for samples, and the injector was in a splitless mode. Helium was used as the carrier gas (with a flow rate of 1.2 mL/min). VOCs were identified by comparison with the mass spectra and retention times of data from libraries. A total of 149 VOCs were investigated, of which 147 were affected by HPP treatment. The total content of volatile compounds differed based on the methods used. The lowest contents of VOCs were observed in HPP at 0 °C, while the highest were obtained in HPP at −35 °C. It was stated that a temperature of 35 °C could reduce the quality of meat, while processing at 0–20 °C could be successfully used and not affect the food quality.

3.4. Ultrasound (US)

The use of ultrasonic waves in meat processing is aimed at tendering the raw material and improving its textural parameters. Considerable tenderness of meat is achieved through the release of myofibrillar proteins from the muscle cells. In addition to the tendering effect, US has an influence on improving the water-binding capacity and cohesiveness of meat [42]. Research by Zou et al. [43] has shown that ultrasonic treatment of beef increases the content of volatile flavors, especially aldehydes, alcohols, and ketones. Similar results were obtained by Bao et al. [44], who analyzed the effect of US on the physicochemical properties of yak meat. Apart from changes in physical properties, US also significantly increased the content aldehydes and ketones.

US is also used in the heat treatment process. Such studies were carried out by Cichoski et al. [45], who assessed the effect of cooking with US on the quality and profile of VOCs of mortadella. On the first day of the experiment, significant differences in the amount of compounds such as hexanoic acid, pentane, β-pinene, caryophyllene, copaene, dimethyl sulphide, diallyl disulphide, nitric acid, ethyl ester, benzene, and 1-propene-1-methylthio-E were observed. These differences intensified during storage, which resulted in the recording of 19 new VOCs.

3.5. Cold Plasma (CP)

CP as a method of food decontamination is being used increasingly often in the food industry. Apart from the influence of this process on microorganisms, the influence of CP treatment on the quality characteristics of meat, including the VOCs profile, is also important [46,47]. Unfortunately, treatment with the use of plasma is associated with the intensification of the fat oxidation process in the raw material, which results in the formation of secondary volatile and non-volatile compounds. These include VOCs such as alcohols, aldehydes, carbonyls, furans, and hydrocarbons [48,49]. In addition, Luo et al. [50] conducted experiments to demonstrate the effect of plasma treatment of water used to cure pork loin. Based on their experience, it was shown that water treatment with plasma not only affects the physicochemical properties of the final product, but also changes the profile of VOCs. The intensity of the process was strongly correlated with the formation of free amino acids, and it also influenced the formation of new volatile compounds in the product. Among them were 3-methylbutanol, hexanal, 2,3-hydroxy-butanone, 2,3-octanedione, and about 20 other volatile compounds. Nevertheless, some volatile compounds have also been shown to be lost through plasma treatment. These changes are most likely related to changes caused by lipid oxidation, Strecker degradation, and Maillard reactions [50]. On this basis, they showed that plasma treatment not only contributed to the decrease in the number of microorganisms on the surface of the meat, but also increased the absorption of oils constituting a component of the protective coating. The beef-coating process itself contributed to the inhibition of fat oxidation and, as a consequence, the decrease in the content of some volatile compounds, including alcohols, esters, ketones, and aldehydes. CP has also found application in removing VOCs from the food industry that may be toxic and/or harmful. The main advantage of this method is relatively low consumption of energy and overall reasonable cost compared to traditional air-consuming methods. Moreover, this technology provides clean air with low concentrations of VOCs at relatively low operating temperatures [51].

3.6. Ozone

Ozone and electrolyzed water (EW) treatments are some of the newest preservation technologies used in the meat industry. A relatively low level of aqueous ozone and electrolyzed water can be used as an economically convenient, safe, and environmentally friendly way to preserve meat products at the final stage of the slaughtering process. These systems were studied in [52] research, and then the EW method was closely examined by Botta et al. [53]

The object of the research [52] was to extend the shelf life of beefsteaks. Methods embracing aqueous ozone containing 6 mg/L and electrolyzed water at 100 mg/L of free chloride were investigated. GCMS analysis of VOCs profile was carried out before the treatment and after 1 and 15 days of storage at 4 °C. Meat samples were extracted using NaCl solution and internal standard, then exposed to SPME fiber. Helium at flow rate of 1 mL/min was used. The identification of VOCs was confirmed by comparison with retention indices of pure standards. VOCs, for which standards were not available, were identified using the mass spectra and retention indices from the literature. Thirty-two volatile substances were detected, of which alcohols, aldehydes, and ketones were the most abundant. It was stated that amounts of volatile compounds varied during storage time, but were not affected by different treatments.

Botta et al.'s [53] study focused on the impact of different dosages of electrolyzed water on the spoilage profile of meat. Preliminary studies showed that lower concentrations of EW (25 and 50 mg/L) were not efficient at reducing microbial spoilage. Only EW at 100 mg/l of free chloride was efficient, so it was utilized in the study. Based on previous studies, 11 VOCs were quantified in the headspace. The analysis was conducted using the procedure used in a previous study [52]. The results showed increasing concentrations during the storage. The VOCs concentration was not affected by the control and experimental treatments, nor by different production runs.

3.7. Pulsed Electric Field (PEF)

PEF is a method used in food industry to control microbiological safety and changes in the characteristics (nutritional, sensory, physicochemical, etc.) of food products. Such possibilities are provided by the use of PEF in the electroporation process. It is a simple, non-toxic method that induces pores in the cell membrane under the influence of short, pulsating pulses of electricity. Kantono et al. [54] is one of the few studies focusing on the influence of PEF on the volatile compounds profile. The authors have shown in their work that some VOCs, including 2-nonanone, 2-pentylfuran, pyrrole, methylpyrazine, 2-ethyl-3-methylpyrazine, and thiophene correlate with the meaty and juicy taste of PEF-treated frozen lamb pieces. In addition, PEF is associated with the formation of amino acids in lamb (threonine, phenylalanine, isoleucine, tyrosine, and methionine) and some volatile compounds (heptanal, 2-ethylfuran, pyridine, dimethyl disulfide, dimethyl trisulfide, and 3,5-diethyl-2-methylpyrazine). On the other hand, it should be noted that PEF may adversely affect lipid oxidation, which results in a change in the profile of volatile compounds [55]. This is especially true for meat that is not refrigerated. Such a discovery was made by Faridnia et al. [56], who, in their work, described changes in the profile of beef *longissimus thoracis et lumborum* and *semitendinosus* volatile compounds caused by an increase in protein and lipid degradation products, such as dimethyl disulfide and 2,3-octanedione. Similar observations were made in Chotphruethipong et al.'s [57] study, where it was found that the use of porcine pancreas lipase (PPL) or lipid hydrolysis in PEF-treated skin prior to papain hydrolysis lowers the level of volatile compounds that are formed as a result of lipid oxidation. Nevertheless, they found that the processing of PEF had an effect on the VOCs profiles of both chilled and frozen pre-processed meat [58].

4. Thermal Processing

4.1. Smoking

Smoking food is one of the oldest methods of preservation. This process is also intended to impart specific sensory characteristics to the product, including a specific aroma. Over the years, smoking methods have evolved from traditional methods based on burning wood to industrial methods. The factors influencing the volatile compound profile of the smoked product include the type of meat, method of smoking and smoke density, the type and moisture of wood used, the process time, and reactions between proteins, carbohydrates and lipids caused by endogenous enzymes or activity of microorganisms [59–62]. The main volatile compounds come from smoking, oxidation, and Maillard reactions, and the oxidation of lipids and their interaction with proteins [63,64]. The method of processing has a significant influence on the process of smoking of meat and meat products. The quality and composition of the smoke is important; this includes, for example, the method of obtaining liquid smoke used industrially [65–67]. Yin et al. [62] compared the effect of traditional and industrial smoking with smoldering smoke and industrial smoking with liquid smoke on the volatile compound profile of harbin red sausages. Eighty-six VOCs were identified, of which phenolics were the most abundant. Sausages smoked with smoldering smoke were characterized by a lower content of volatile compounds than products smoked with liquid smoke. These differences were noted mainly in the content of phenols, alcohols, aldehydes, and ketones. Research by Guo et al. [59] proved that the most volatile compounds were detected in smoked bacon using the paper method. The paper method allowed us to obtain higher contents of aldehydes, esters, alcohols, and alkanes, than those found in the samples of smoked wood and liquid smoke. On the other hand, the bacon smoked with wood and liquid smoke had a higher phenolic content.

The characteristics of VOCs formed during the smoking of meat and meat products should begin with the analysis of the smoking process with wood smoke. Wood smoke is produced by pyrolysis of wood at elevated temperatures and reduced oxygen levels. It has the form of an aerosol composed of three phases of compounds in the gas phase: particles, liquid drops, and solids. There are over 400 VOCs found in wood smoke, of which alcohols, acids, carbonyls, esters, furans, 16 lactones, and phenols have been identified so far [61]. In the case of burning a smokehouse with wood chips, the type of wood used is important. The work of Zhang et al. [68] presents the research of the analysis of the influence of the addition of apple, pear, and tea leaves wood on the VOCs profile of smoked chicken drumsticks. The smoking process itself significantly enriches the aroma profile with new VOCs. The degradation of alcohols to acids, aldehydes, and esters during smoking contributes to a decrease in the content of this group of compounds in smoked products compared to raw chicken. Among them, we can distinguish compounds such as linalool and 1-octene-3-ol, the amount of which decreased after treatment. In all samples, regardless of the type of wood used, the content of alcohols and aldehydes was similar. Nevertheless, some differences were stated in the content of ketones, acids, phenols, and furans. The use of pear chips and tea can significantly increase the acid content, and apple trees increase the furan content. The amount of phenols, similarly to alcohols after smoking, decreased. In another study, Merlo et al. [69] compared the volatile profile of bacon smoked with smoke from *Acacia mearnsii* and *Eucalyptus citriodora*. The results showed that the use of *Eucalyptus citriodora* increases the phenol content and consequently lowers the hexanal concentration while inhibiting lipid oxidation. A similar phenomenon can be observed when using liquid smoke from different types of wood [70]. On the other hand, the use of maguey leaves (*Agave salmiana*) when cooking lamb produces volatile compounds from the group of aldehydes, terpenes, and benzene [71]. An interesting correlation was observed when analyzing volatiles in commercially smoked chickens. Smoking with sawdust from fruit trees increases the phenolic content, while sugar lowers the amount of furans, which contribute to the sweet caramel aroma [72]. The addition of sugar, tea, and rice significantly influences the profile of aromatic compounds responsible for the smoked, bitter, and caramel aromas.

The species and breed of animals are also factors that determine the formation of specific volatile compounds in smoked products [73]. This issue was investigated by Deng et al. [74], who analyzed volatile compounds formed in smoked bacon obtained from two different crosses of pigs (white pig and black pig). The results of their work proved that smoked black pig products had fewer volatile compounds than those of the white pig. Among them, the authors detected aldehydes, ketones, alcohols, esters, hydrocarbons, acids, fourteen phenols, aromatic hydrocarbons, nitrogen-containing compounds, and furans. These differences are mainly due to the basic composition of meat, including the amount of fat, and differences in lipid and protein degradation in both non-enzymatic and enzymatic reactions. Even the element of the carcass will play a role in shaping the volatile compound profile. Chang et al. [75] analyzed the aromatic content of chicken rings and skin after the sugar-smoking process. The higher content of substances reacting with thiobarbituric acid and the higher ratio of polyunsaturated fatty acids to saturated fatty acids caused that the skin was characterized by a higher content of volatile compounds than the breast. The volatile fingerprint results revealed that the heterocycles were a distinctive flavor developed during the smoking process of sugar. In contrast, hexanal, nonanal, furfural, 5-methyl-2-furancarboxaldehyde, and 2-acetyl-5-methylfuran were the main volatile substances in chicken skin. This is due to the lipid oxidation and caramelization reactions.

Pre-treatment, such as pickling or salting before smoking, has a significant impact on the aromatic compounds produced. Among these pre-treatments is the partial replacement of NaCl by chloride salts during the treatment of Cecina deer. Such action significantly reduces the amount of acids and furans in the final product profile [76].

4.2. Cooking Techniques

The aroma characteristic of meat after heat treatment is obtained from VOCs derived from thermally induced reactions occurring during heating, mainly as a result of Maillard reactions, lipid oxidation, interaction between Maillard reaction products with lipid-oxidized products, and vitamin degradation [77]. Proteins react with sugars, resulting in Maillard reaction products such as carbonyls, nitrogen and sulfur containing compounds, which can interact each other or with other reactive compounds to yield compounds such as pyrazines, thiazoles, and thiophenes [16].

Yu et al. [78] analyzed chicken meat after heat treatment using three methods (frying, boiling, and roasting). VOCs were analyzed using the GC-IMS method. A total of 26 VOCs were detected. Phenylacetaldehydes were the main volatile flavor compounds in boiled chicken; 3-butanedione, etc., were the main volatile flavor compounds in fried chicken; while 3-methylbutyraldehyde, etc., were the main volatile flavor compounds in roasted chicken.

Zhang et al. [68] evaluated the impact of temperature and time *in sous vide* method on the quality parameters of duck meat. The flavor profile of meat was analyzed using GC-MS. The concentrations of hexanal, heptanal, octanal, (E)-2-octenal, nonanal, cis-4-decenal, decanal, (E,E)-2,4-nonadienal, 2,4-decadienal, (E,E)-2,4-decadienal and 1-octen-3-ol in samples cooked at 70 °C for 6 h or 12 h were relatively higher than in other samples.

4.3. Drying

Common meat preservation treatments include salting and drying. It is known that the volatile compounds of dried meat products are formed by numerous and complex reactions. Most of these reactions occur during the maturation phase and originate mainly from carbohydrate fermentation and lipolytic and proteolytic processes. The liberated free fatty acids, amino acids, and peptides then serve as substrates for oxidation, and Strecker and Maillard reactions result in a wide variety of volatile compounds with distinct aromatic notes and/or odor thresholds [79]. The formation of VOCs during the application of preservative treatments is mainly influenced by time, temperature, drying method, or salt concentration. Drying methods include spray drying (SD) (a method used to create powders such as chicken [80]), vacuum drying (VD), microwave vacuum drying (MVD), infrared vacuum drying (IFVD), viz hot air drying (HD), vacuum freeze-drying (FD), among others. However, it was found that the drying methods (HD, VD, MVD, and FD) caused damage to 8-carbon (C8) compounds, especially to a significant extent for eight-carbon alcohols. Moreover, each drying method has been shown to generate greater amounts of volatile compounds belonging to different groups: HD contributes to the generation of more ester compounds, MVD contributes to the generation of more aldehyde compounds, FD contributes to the generation of more hydrocarbon compounds, and VD contributes to the generation of more ketone compounds for the test material chicken and white Hypsizygus marmoreus [80,81]. Depending on the duration, drying can also generate different levels and types of volatile compounds. Volatile compounds of dried deer loin after 30 days and after 60 days showed that the change in the profile of volatile compounds over time is determined by changes in the processes of lipolysis, proteolysis, and oxidation such as alcohols (1-hexanol, 1 octen-3-ol), aliphatic aldehydes, branched aldehydes, and furans [71]. The drying temperature affects the composition of volatile compounds by altering biochemical reactions: it affects the oxidation of fatty acids, the growth of microorganisms (generation of hydrolases and oxidases), and the activity of endogenous enzymes. An increase in temperature contributes to an increase in VOCs belonging to the group of alcohols, aldehydes, and ketones [82].

The salting process prolongs the shelf life of meat products. Higher salt content slowed the formation of alcohols and branched-chain aldehydes from amino acids such as valine, isoleucine, and leucine formed on the Strecker degradation reactions, while it promoted the formation of aldehydes from fatty acids. Moreover, salt has the effect of reducing proteolysis activity by modifying the polarity of the protein surface. The increased amount of salt used may result in reduced formation of volatile flavor-active substances in dried turkey ham [83]. In addition, an analysis of the literature showed the occurrence of a positive correlation between salt content and total aldehydes, and a negative correlation with total alcohols, alkanes, and ketones. Salt-curing methods such as static brining, pulsed pressure salting, and vacuum tumbling curing also affect the formation of volatile compounds in meat products. Research conducted by Chen et al. [84] showed that vacuum drying reduced the values of volatile compounds (especially 1-hexanol, 1-octen-3-ol, hexanal, and 2,3-octanone) compared to the other methods. Due to the formation of unpleasant odors such as 1-hexanol and 1-octen-3-ol, attention should be paid to the selection of curing methods in terms of the taste of processed meat products and human health. Nowadays, due to the trend of reducing NaCl in food products, various substitutes (KCl, flavor enhancers, $CaCl_2$) are used; however, in the study, it was found that sodium substitutes had a more significant effect on the odor profile [85]. The combination of salting and drying processes depending on the species of meat (deer, bovine, goat, horse) generated different amounts and odor levels of volatile compounds, obtained through the effect of the following processes: lipid oxidation, amino acid degradation, carbohydrate fermentation, and microbial esterification. In addition, the physical conditions of the product undergoing shelf-life extensions such as size and shape affect the availability of oxygen, and thus affect the process of auto-oxidation [86].

5. Conclusions

There are many factors affecting the content of VOCs in meat. Meat volatile compounds are created during heat treatment and are a result of the interactions of precursors in the raw meat. These actions contain pyrolysis of peptides and amino acids, degradation of ribonucleotides and sugar, Maillard reactions, Strecker degradation, lipid oxidation, degradation of thiamine and lipids, as well as microbial metabolism. The generation of volatile compounds is carried out and divided into non-thermal and thermal processes. Modern and advanced methods such as pulsed electric field, ultrasounds, cold plasma, and ozone have an effect on the final flavor of meat and meat products.

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