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Review Paper / Derleme Makale

Effect of Advanced Cooking Methods on Formation of Toxic Compounds in Meat

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ABSTRACT

Meat is an essential component of human nutrition and is prepared using various cooking techniques to ensure its microbiological safety and enhance its sensory qualities. However, conventional cooking methods like grilling, deep-frying, and pan-searing often involve extended heat exposure, which can result in the production of harmful toxic compounds such as polycyclic aromatic hydrocarbons, heterocyclic amines, and acrylamide that may pose health risks. Moreover, the high temperatures and prolonged cooking times, typical of these conventional methods, can cause a reduction in the nutritional content of meat. In recent years, research has focused on innovative methods that can minimize the formation of toxic substances in meat while preserving its nutritional value and offering safer cooking alternatives. Among these advanced cooking technologies, microwave heating, ohmic heating, sous-vide cooking, and air-frying have attracted increasing interest. Compared to conventional methods, these techniques present important benefits, including improved product quality and efficiency, faster processing times, energy savings, and lower production costs. This review discusses advanced cooking technologies and their principles, highlighting their influence on the formation of toxic compounds in meat in comparison with conventional cooking practices.

Keywords: Meat, Cooking methods, Quality, Advanced techniques

İleri Pişirme Tekniklerinin Ette Toksik Bileşik Oluşumuna Etkisi

ÖZ

İnsan beslenmesinde önemli bir besin kaynağı olan et, mikrobiyolojik güvenirliliğinin sağlanması ve organoleptik özelliklerinin geliştirilmesi amacıyla çeşitli yöntemlerle pişirilerek tüketilmektedir. Ancak etin pişirilmesinde kullanılan ızgara, yağda kızartma, tavada pişirme gibi geleneksel yöntemlerde uzun süre yüksek ısı uygulanmasından dolayı, polisiklik aromatik hidrokarbonlar, heterosiklik aminler ve akrilamid gibi insan sağlığı açısından tehlikeli toksik bileşikler oluşabilmektedir. Bunun yanı sıra geleneksel pişirme yöntemlerinde kullanılan uzun süre ve yüksek sıcaklık etin besleyici değerinde kayıplara neden olmaktadır. Son zamanlarda etin besin değerinde minimum kayıpla birlikte toksik bileşiklerin oluşumunu azaltacak daha güvenli pişirme sağlayacak ileri teknikler ile ilgili çalışmalar popülerlik kazanmıştır. İleri pişirme yöntemleri arasında mikrodalga ısıtma, ohmik ısıtma, sous-vide pişirme ve air-fryer teknolojileri dikkat çekmektedir. Geleneksel yöntemlere kıyasla bu yöntemlerin ürün kalitesini ve verimliliğini arttırması, işlem süresinin kısa olması, enerji tasarrufu sağlaması, işlem maliyetini azaltması gibi avantajlarından dolayı önemli bir potansiyele sahip olduğu ifade edilmektedir. Bu derlemede ileri pişirme teknikleri, uygulama mekanizmaları, ette toksik bileşik oluşumu üzerine etkileri geleneksel yöntemlerle kıyaslanarak irdelenmiştir.

Anahtar Kelimeler: Et, Pişirme yöntemleri, Kalite, İleri teknikler

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INTRODUCTION

During cooking, the tenderness of meat increases due to the shrinkage of muscle fibers and the reduction of adhesion between fibers, resulting in the collagen tissue dissolving to form gelatin, especially at temperatures between 40-60°C [1]. However, when the cooking temperature rises to a temperature between 60 and 90, longitudinal shrinkage of muscle fibers increases water loss, negatively affecting the texture [2]. Furthermore, high temperatures during cooking accelerate oxidation reactions. Lipid oxidation occurs as unsaturated fatty acids undergo oxidation during meat cooking, shortening the shelf life of meat, releasing unwanted odor and flavor compounds, causing nutrient loss, and leading to color and texture abnormalities, which adversely affect quality [3].

Throughout the cooking process, chemical contaminants such as polycyclic aromatic hydrocarbons, heterocyclic amines, and acrylamide, which pose significant risks to human health, can also form in the composition of the meat depending on many factors such as method, temperature and application time [4]. Polycyclic aromatic hydrocarbons (PAHs) are organic compounds released as a result of incomplete combustion of organic materials, which can persist in the environment for extended periods, causing environmental pollution and disrupting biological balance [5]. PAHs are a major concern due to their confirmed or potential adverse health impacts. Regulatory agencies have classified high molecular weight PAHs, such as benzo[a]pyrene (BaP), as priority pollutants because of their significant toxicological relevance [6]. Among foods, meat is considered one of the highest-risk sources of PAHs formation. PAHs levels in cooked meats vary depending on factors such as cooking method, type of fuel, cooking temperature and duration, distance from the heat source, and fat content of the food [7-9]. Studies have shown that smoking, frying, and grilling methods result in higher levels of PAHs formation, whereas boiling and baking methods result in lower levels of PAHs formation [10, 11]. Heterocyclic amines (HAs) are mutagenic/carcinogenic compounds formed when meat is cooked at high temperatures, especially during pan frying or charcoal grilling [12]. It has been reported that HAs can be 100 times more mutagenic than aflatoxin B1 and 2,000 times more mutagenic than BaP on an equal mass basis [13]. HAs level can be reduced by avoiding prolonged exposure to high temperatures and preventing the surface from coming into direct contact with flames while cooking meat [14]. Acrylamide, chemically known as 2-propenamide (C_3H_5NO), is a water-soluble compound commonly present in foods with high carbohydrate content like potato and grain-based products. Acrylamide is found in various quantities in many foods, except for boiled or raw food. Cooked carbohydrate-rich foods were found to contain higher levels of acrylamide (150-4000 µg/kg) compared to cooked protein-rich foods (5-50 µg/kg) [15]. Many foods, particularly those high in carbohydrates (starch), amino acids (asparagine), and oils (glycerol is converted to acrolein) produce acrylamide when they are heated to temperatures above 120°C during the thermal frying process [16]. The International Agency for Research on Cancer (IARC) [17] has identified acrylamide as a potential human carcinogen, and it is also formed during the frying of chicken [18].

In conventional (traditional) cooking methods, the use of prolonged time and high temperatures generally leads to losses in the nutritional value of the meat. Additionally, the cooking method and duration may result in the formation of toxic compounds that may pose a threat to human health. To eliminate these risks, recent studies have focused on the use of alternative advanced cooking methods such as microwave heating, ohmic heating, sous-vide, and air-frying technologies to produce safer, minimally processed foods with high nutritional value [19, 20]. In advanced cooking methods, thermal energy is produced directly within the food, ensuring homogeneous distribution of heat throughout the food. The aim of using these methods is to improve product quality, shorten processing times, reduce costs, and increase efficiency by decreasing water and energy consumption [21]. In this study, the effects of traditional and advanced cooking technologies on formation of toxic compounds in meat were reviewed.

EFFECT OF TRADITIONAL MEAT COOKING METHODS ON FORMATION OF TOXIC COMPOUNDS

Grilling

Grilling is a dry cooking method that utilizes direct radiant heat. In this method, heat sources such as oven grills, electric grills, or charcoal grills can be used. Since the heat spreads from one direction, it is necessary to turn the meat during cooking [22]. In the charcoal grilling method, one of the biggest risks that arise from cooking at very high temperatures with charcoal is the formation of PAHs [23]. It has been reported that in grilled meat products cooked at high temperatures, PAHs compounds are formed as a result of pyrolysis of fat dripping onto the charcoal and these compounds are transferred to the meat surface along with the smoke [23, 24]. The levels of PAHs in cooked meats vary depending on the preparation and cooking method, temperature, duration, distance of the meat from the heat source (direct or indirect), and fat content (Table 1) [8, 25].

To reduce or prevent the formation of PAHs in grilled meat, avoiding direct contact with flames, minimizing exposure to smoke, preventing the burning of fat, removing dripping fat, avoiding excessively high cooking temperatures, and selecting the appropriate distance from the heat source are crucial [9]. In a study examining the effects of different cooking methods (boiling, frying, oven grilling, electric grilling and charcoal grilling) on the formation of PAHs compounds in various types of meat (beef, lamb, chicken, turkey), the concentration of PAH4 compounds BaP, benzo(a)anthracene (BaA), benzo(b)fluoranthene (BbFlu), chrysene (Chr)) was found to vary depending on the structure of the meat and the cooking methods. The highest PAH4 concentrations ranged between 1.10

and 3.30 µg/kg was found in chicken meats cooked on the grill [11]. Another way to reduce PAHs compounds in meat is by applying different marinades before the cooking process, which has been shown to be quite effective in reducing the formation and concentration of PAHs in cooked meats [27, 28]. In a study examining the effect of different tea plant marinades on the formation of PAHs in grilled chicken drumsticks cooked using different methods (charcoal and electric), it was found that marinated drumsticks with white tea and cooking them on an electric grill significantly reduced the formation of HCAs (from 13.15 ng/g to 10.08 ng/g) and BaP (from 13.15 ng/g to 0.17 ng/g) compared to wood charcoal grilled drumsticks ($P<0.05$) [29].

Table 1. The major factors influencing the PAH formation in meat [26, 27]

Type of grill	Temperature and time
Electric < Gas ≤ Briquettes=Charcoal < Wood	Low temperature < High temperature
No dripping fat < Dripping fat	Short grilling time < Long grilling time
Long distance from heat < Short distance	
Vertical heat source < Horizontal heat source	
Type of food	**Preparation of the food**
Low fat < High fat	Frequent turning < No turning
Smooth/sealed surface < Rough surface	Marination with antioxidants < No marination
Low protein < High protein	Precooking of food < No precooking

Saute Cooking

Saute cooking is a method where small pieces of meat are cooked in a pan with a small amount of oil. In this method, the pan is heated to 160-240ºC before cooking, thus preventing the meat from sticking to the pan and the water in the meat from leaking out during the sealing process [23]. It is stated that factors such as cooking method, temperature, duration, pH, and fat content play significant roles in the formation of mutagenic and carcinogenic heterocyclic amines in saute cooking method [30].

In a study, various cooking methods (deep fat frying, pan frying, charcoal grilling, and roasting) on the formation of heterocyclic amines in chicken and duck breast meats were investigated. The results showed that chicken breast cooked by charcoal grilling had the highest total HAs content (112 ng/g), followed by pan-fried (27.4 ng/g) and deep fried (21.3 ng/g), while the lowest formation of HAs was observed in roasted chicken breast (4 ng/g). Similarly, for duck breast pan frying resulted in the highest HAs content (53.3 ng/g), followed by charcoal grilling (32 ng/g), deep frying (13.9 ng/g), while the lowest HAs formation was observed in roasted duck breast (6.8 ng/g) [31].

Deep Fat Frying

Deep fat frying is a method of cooking meat by immersing it in oil at 150-190°C [32]. During frying, various physical and chemical changes occur in the color and structure of the oil [33]. The primary degradation products in frying oil are non-volatile polar compounds, triacylglycerol dimers, and polymers. The change in color of the oil is associated with oxidation, polymerization, and the formation of carbonyl compounds [34]. Deep fat frying is a method commonly used in large-scale food production operations. The oils used in this process tend to degrade more quickly than those used for home frying, primarily due to their prolonged use [32].

Since oil can break down and produce smoke at high temperatures, oil with low smoke points should not be used for frying [35]. Due to the application of high temperatures, carcinogenic compounds such as PAHs, HAs and acrylamide can form in meat [23]. In the frying process, the formation of carcinogenic compounds increases as the time increases [34]. Additionally, the toxic compounds produced by the repeatedly using cooking oil at high temperatures during frying pose a health risk [34]. HAs are formed during frying in oil and repeated use of oil leads to an increase in the amount of toxic components [32, 36].

In a study conducted by Ghasemian et al. [37], hamburgers prepared from beef were fried in sunflower oil at 180°C and 200°C for 4 and 6 min. Their results indicated that acrylamide levels reached 40 ppb in a beef burger fried in sunflower oil at 180°C for 4 min, while 85 ppb of acrylamide was detected in a beef burger fried at 200°C for 6 min. As a result of the study, it was reported that an increase in temperature and cooking time led to an increase in acrylamide content of hamburgers. In another study, various cooking methods (microwave, baking, deep fat frying, and pan frying) were applied to heat-treated croquettes filled with meat. As a result, acrylamide concentrations of 360 µg/kg, 285 µg/kg, and 298 µg/kg were detected in baked, pan fried, and deep fat fried croquettes, respectively, while the highest level of acrylamide formation (420 µg/kg) was reported in the microwave cooked croquettes [38].

Boiling

Boiling is a method of cooking food in a liquid at temperatures above 100°C. This can be achieved by rapidly boiling the liquid or by gently simmering it at temperatures below the boiling point. It is known that the formation of carcinogenic heterocyclic amines is lower in boiled meats compared to grilling, frying, and sauteing methods. In the boiling method, the aim is to prevent drip loss and physical changes in the meat by retaining its juice. However, the addition of more water than necessary during cooking causes vitamin and mineral losses, as well as color and flavor deterioration [35].

Solyakov and Skog [39] reported that the content of HAs in poultry meat samples was lower (0.5 ng/g) when boiled at low temperatures (<100°C) compared to cooking at higher temperatures, and HAs formation increased with rising cooking temperature. In another study, the effect of different cooking methods (smoking, grilling, and boiling) on the formation of PAHs in processed meats was examined. As a result, it was reported that the highest level of PAHs (2.79 µg/kg) was found in smoked meats and the lowest level of PAHs (0.99 µg/kg) was determined in boiled meats [40].

Baking

Baking is a method that evenly cooks food by transferring heat directly or through convection. The baking method is widely used in the food industry [41]. The quality characteristics and microbial safety of meat are affected by the baking process [42]. High cooking temperatures enhance the color and flavor of meat, shorten the cooking time, but reduce its juiciness and cause it to gain a hard texture [43]. In a study, the formation of PAHs in beef and pork during grilling and baking were investigated. The results indicated that the concentration of PAHs depended on the cooking method and the type of heat source used, with the highest concentration of PAHs (10.2 µg/kg) observed in charcoal grilling [44].

EFFECT OF ADVANCED MEAT COOKING METHODS ON FORMATION OF TOXIC COMPOUNDS

Microwave Heating

Microwave heating is a dielectric heating method commonly used in industry for cooking or reheating food quickly in households. Microwave energy is a non-ionizing electromagnetic radiation with a frequency range of 300 MHz to 300 GHz [21]. In microwave heating method, the formation of a homogeneous electromagnetic field allows energy to penetrate directly into the food, enabling volumetric and rapid heating. In food processing, operations such as heating, drying, sterilization, and thawing can be performed more efficiently with microwave technology, allowing for greater energy efficiency and shorter processing times [45]. The principle of microwave cooking involves converting electromagnetic energy into thermal energy within the meat. During the cooking process, microwave energy is absorbed through the rotation of water molecules and the movement of ionic components in the meat. Therefore, the water content and the dissolved ion content play crucial roles [46]. Compared to traditional heating methods, microwave heating provides homogeneous heat treatment [47].

In a study, the effect of different cooking methods on the concentration of HAs in chicken and beef satays was investigated. Beef and chicken satays were subjected to grilling, microwave pre-treatment before grilling, and microwave followed by deep frying. The results indicated that chicken satays cooked by charcoal grilling had the highest total HAs content (126.59 ng/g), followed by microwave-charcoal grilled (81.69 ng/g), while the lowest formation of HAs was observed in microwave-deep fried chicken satays (3.44 ng/g). Similarly, for beef satays charcoal grilling resulted in the highest HAs content (140.68 ng/g), followed by microwave-charcoal grilling (81.31 ng/g), while the lowest HAs formation was observed in microwave-deep fried beef satays (2.51 ng/g) [48].

Ohmic Heating

Ohmic heating is an advanced electro-heating technique in which alternating electric current is passed through food to achieve heating. In ohmic heating, food is used as a resistor, allowing alternating current is passed through it, thereby converting the electrical energy into heat energy [49]. Generally, ohmic heating is applied to foods at frequencies between 50-60 Hz [21]. Ohmic heating offers many advantages such as preserving product quality, reducing cooking loss, requiring low-cost, high-energy efficiency, and being environmentally friendly due to its ability to provide rapid and uniform heating [20]. The heat generation that occurs in the ohmic heating method varies depending on the thermal conductivity of the food and the voltage gradient used during heating. In ohmic heating, as the applied voltage gradient increases, the time required for the sample to reach the desired temperature decreases. Foods with high electrical conductivity heat up more quickly [50].

It has been stated that ohmic heating is effective on color stability as well as increasing protein coagulation and aggregation in meat [51]. In a study reported by Zell et al. [20], the effects of ohmic heating and steam cooking on beef quality were investigated. The results indicated that samples cooked with ohmic heating had a lighter color and less cooking loss compared to those cooked with steam, but they exhibited a firmer texture. Another study explored the impact of low-temperature long-time (72°C, 15 min), high-temperature short-time (95°C, 8 min) ohmic heating, and steam heating (80°C, 105 min) on meat quality. The findings revealed that meats subjected to ohmic heating had higher L^* and lower cooking loss values compared to those subjected to steam heating [52].

Sous Vide

Sous vide is a cooking technique of French origin where vacuum-sealed meat, either raw or pre-cooked, is cooked in a controlled environment of low temperature (60-95°C) with circulating water or both heat and steam [53, 54]. After cooking, the product can be served directly or grilled or pan fried [55]. Compared to traditional methods, the sous-vide method uses lower temperatures and longer cooking times [56]. Studies have reported that this combination enhances the activity of proteolytic enzymes in meat, leading to the release of free amino acids and increased tenderness [57, 58]. It has been reported that in sous vide cooking, there is less loss of nutritional components like vitamins and minerals in meat compared to traditional cooking methods such as frying, microwaving, oven cooking, and grilling [59, 60]. Cooking meat at high temperatures can lead to the formation of toxic and harmful substances such as HAs, as well as a loss of nutritional value [61]. In sous-vide cooking technology, the formation of harmful substances is reduced, and the nutritional value of meat is preserved, as cooking takes place in a vacuum packaging environment and at low temperature [62].

There are two main points that distinguish sous-vide cooking from other methods. First, the food being cooked is vacuum-sealed, which minimizes contact with air and thus preventing oxidative spoilage during cooking or subsequent storage. Second, the food is cooked under controlled conditions at a constant temperature, ensuring that the temperature remains the same throughout the cooking process, both at the center and on the outer surface [62, 63]. Traditional cooking methods often result in temperature differences between the center and the surface of the food. In the sous-vide method, controlled temperature and time parameters are used, allowing products to be easily prepared to the desired level of doneness and ensuring consistent food quality every time [64]. Additionally, because the meat is cooked in a vacuum-sealed package, the heterogeneous temperature and color distribution observed in traditional cooking methods are eliminated, and no additional processes such as stirring or flipping are needed to ensure uniform cooking [65]. The biggest problem in cooking meat at low temperatures for a long time using the sous-vide method is its pink appearance due to the lack of Maillard Reaction on the surface of the cooked meat [66]. To prevent this, the surface of the meat cooked with sous-vide is fried to induce the Maillard reaction [56].

In a study, the formation of HAs was examined in beef samples cooked using sous-vide, boiling, and frying methods at different temperatures and durations. The results showed that total HAs content of the samples ranged from 0.032 ng/g to 0.940 ng/g. The highest level of HAs was detected in samples cooked using the frying method, while the lowest level was found in samples cooked using sous-vide at 75-85°C for 120 min. Additionally, it was reported that maintaining a constant temperature and increasing the cooking time in sous-vide cooking resulted in higher levels of HAs in the samples [67].

Air-Frying

Air-frying is a new technology that cooks food by circulating hot air around it, ensuring even contact between the food and the oil droplets [68]. The mechanism of the air-frying is based on the transfer of heat from the circulating hot air to the food. During the cooking process, dehydration from the surface occurs, resulting in a crispy texture and unique sensory and textural properties in the final product. Air-frying is considered a relatively healthier frying method compared to traditional methods due to lower oil absorption [69]. Compared to deep fat frying, foods cooked in an air fryer contain 70-80% less fat [70].

Recent studies have reported that excessive fat intake increases the risk of hypertension and obesity [71]. Therefore, new methods have been investigated to reduce the fat content of fried products without compromising product quality, and it has been reported that air-fryer cooking method is effective in maintaining food quality and safety [70].

In a study conducted by Lee et al. [72], the formation of acrylamide and PAHs in chicken breast, thigh, and wing samples thawed using different methods (microwave, refrigerator and immersion in water) and cooked using air frying and deep fat frying methods was investigated. Their results revealed that deep-fat-fried chicken meat had higher levels of acrylamide (n.d.-6.19 µg/kg) and total PAH (2.64-3.17 µg/kg) compared to air-fried chicken meat (n.d.-3.49 µg/kg and 1.96-2.71 µg/kg). It was also observed that the thawing method did not significantly affect the formation of acrylamide or PAHs ($P>0.05$) in chicken meat. They concluded that the air-frying method could reduce the formation of acrylamide and PAHs in chicken compared to the deep fat frying method.

TRADITIONAL VERSUS ADVANCED COOKING METHODS

Traditional cooking methods can lead to the formation of harmful compounds (HAs, PAHs etc.) as previously mentioned. In contrast, advanced cooking methods may help reduce the production of these undesirable substances [73]. Therefore, various advanced technologies have been developed and applied to meat to mitigate the harmful effects of high temperatures while enhancing meat quality, as shown in Table 2.

CONCLUSION

Meat, which is an essential source for a balanced nutrition and requires thermal processing for consumption, plays a significant role in the intake of carcinogenic compounds into the body. Exposure of meat to high temperatures for extended periods can lead to the formation of carcinogenic compounds such as PAHs, HAs and acrylamide, which adversely affect the eating quality of meat. Cooking conditions are one of the most important parameters affecting the formation of these compounds. For this reason, it is very important to choose the appropriate cooking method, apply the controlled cooking process at low temperatures, avoid cooking directly over the flame, prevent the burning of meat fat and pay attention to the distance from the heat source. It is predicted that advanced cooking methods may be preferred as alternative safe cooking methods offering advantages over traditional methods including energy savings due to shorter processing times, protection of product quality, reduction or prevention of toxic compound formation, decreased cooking losses, lower oil absorption, and more homogeneous temperature, and color distribution.

Table 2. Comparison of the advantages and disadvantages of different meat cooking methods

Cooking Methods	Advantages and Disadvantages	References
Grilling	Processing at temperatures above 200°C poses a risk of HAs formation, while prolonged cooking further enhances the likelihood of PAHs formation, including higher BaP levels	[23]
Saute Cooking	PAHs and HAs formation from prolonged cooking at high temperature	[23]
Deep Fat Frying	The acrylamide levels increase when frying oil is reused multiple times	[33]
Baking	Dry air flow causes the evaporation of surface water, leading to surface drying and formation of harmful compounds such as acrylamides, PAHs and HAs, which accumulate on the meat surface	[43]
Microwave Heating	Fast processing time reduces PAHs formation	[45]
Ohmic Heating	Reduction of PAHs and HAs formation due to direct and homogeneous cooking	[20]
Sous Vide	Reduction in PAHs and HAs formation due to prolonged cooking at temperatures between 60-95 °C	[56]
Air-frying	Reduction in PAHs and HAs formation due to lack of direct flame contact	[70]

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