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Meat Technology — Special Issue 66/3

www.meatcon.rs ▪ www.journalmeattechnology.com

UDK: 615.9
641.526.3:637.5

ID: 179668233

https://doi.org/10.18485/meattech.2025.66.3.6

Review Paper

Mechanisms, exposure, and reduction strategies of polycyclic aromatic hydrocarbons in charcoal-grilled meat

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ARTICLE INFO

Keywords:
Polycyclic aromatic hydrocarbon
Charcoal grilling
PAH formation mechanism
Mitigation strategies
Health risk and exposure

ABSTRACT

Meat cooked on a charcoal grill produces polycyclic aromatic hydrocarbons (PAHs) through pyrolysis, incomplete combustion, and fat dripping onto heat sources. High meat consumption and the use of charcoal in traditional Serbian grilling techniques encourage the formation of PAHs, especially carcinogenic substances like benzo[a]pyrene. PAH levels are greatly influenced by variables like fuel type, grilling method, temperature, and fat content. Indirect grilling, pre-treatments, and marinades high in antioxidants all successfully lower PAH contamination. Dietary PAHs have been linked by epidemiological data to an increased risk of cancer, and grilling environments present additional health risks due to occupational exposure. Preventive measures must be put in place to reduce exposure to PAHs and the health risks they pose. This review emphasizes the pressing need for additional research and public health initiatives to lower PAH exposure while maintaining culinary customs.

1. Introduction

According to 2022 data, the average annual meat consumption worldwide was about 44.14 kg per person. In the European Union, it reached around 78.83 kg. Serbia's consumption, at approximately 79.37 kg per person, is close to the EU average (*OurWorldInData et al.*, 2019). Despite economic challenges, Serbia maintains high meat consumption. This shows the strong influence of cultural and traditional habits on dietary choices, often regardless of economic status. Meat has been a staple in the Serbian diet for centuries. Grilling is seen as a cultural symbol and social activity, especially with dishes like "pljeskavica" and "ćevapčići" (*Baltic et al.*, 2018; *Brankov et al.*, 2017; *Stevanović et al.*, 2016; *Tomašević et al.*, 2023; *Trovic et al.*, 2021). Grilling in Serbia usually involves cooking quickly at high temperatures using charcoal or wood. This can create polycyclic aromatic hydrocarbons (PAHs), which are chemical compounds that may cause cancer (*Du et al.*, 2025; *Kartalović et al.*, 2022). PAHs result from the incomplete burning of organic material and are especially common in smoked and grilled meat products (*Kim et al.*, 2021; *Ma et al.*, 2024). Epidemiological studies suggest a connection between PAH exposure and higher risks of several cancers, including colorectal and

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Paper received July 28th 2025. Paper accepted August 26th 2025.
The paper was presented at the 63rd International Meat Industry Conference "Food for Thought: Innovations in Food and Nutrition" – Zlatibor, October 05th-08th 2025.
Published by Institute of Meat Hygiene and Technology – Belgrade, Serbia.

lung cancer (*Cross et al*., 2007; *Farvid et al*., 2021; *IARC*, 2010). Given the importance of meat in Serbian cooking and the common grilling practice, it is essential to assess consumer exposure to PAHs and the related health risks from eating grilled meat.

2. Mechanisms of PAH formation during grilling

Although the specific process involved in PAH formation is yet to be established, three mechanisms are available for PAH formation from food when undergoing grilling: (1) pyrolysis of organic materials, (2) incomplete fuel combustion and (3) dripping of fat from food onto the heat source (*Du et al*., 2025; *Duedahl-Olesen and Ionas*, 2022; *Palade et al*., 2023). Organic materials like carbohydrates, lipids, proteins and others play an imperative role in PAH formation (*Du et al.*, 2025; *Zhang et al*., 2021). This process is substrate-dependent: carbohydrates degrade through caramelization and pyrolysis, while proteins and lipids contribute via Maillard reactions and thermal breakdown (*Hu et al*., 2021). At high temperatures (>200°C), these compounds break down to yield low-molecular-weight light rings and highly reactive intermediate free radicals (*Singh et al*., 2023). The light rings and free radicals combine to yield stable polynuclear aromatics, which then condense to form PAHs via the Diels-Alder reaction (*Llamas et al*., 2017). Additionally, unsaturated intermediates formed during lipid or sugar pyrolysis can undergo ring closures and condensation facilitated by thermal energy and radical recombination (*Hu et al*., 2021). Moreover, the Maillard reaction, an intricate chemical reaction in the course of thermal treatment of meat products, has a significant function in pyrolysis of organic matter towards the generation of PAHs in grilled food (*Nie et al*., 2018a). Pyrolysis of protein in meat gives rise to free amino acids which, through the Maillard reaction, react with reducing sugars to form intermediate products, such as Amadori rearrangement products (ARPs) (*Ishak et al*., 2022). Intermediate products continue to decompose to form PAHs, such as phenanthrene (Phe), pyrene (Pyr), and benzo[a] pyrene (BaP) (Britt et al., 2004). This transformation is influenced by pH, water activity, and reaction time, which modulate the degradation pathways of Maillard intermediates (*Hu et al*., 2021). One of the key pathways for PAH formation is the incomplete combustion of fuel, which generates reactive hydrocarbon radicals and low molecular weight (LMW) PAHs (*Afe et al*., 2020; *Iko Afé et al*., 2020). During this process, several mechanisms are involved, including the hydrogen abstraction-carbon addition (HACA) mechanism (*Kislov et al*., 2013). As the temperature increases, free radicals and LMW PAHs undergo cyclization and polymerization reactions, ultimately forming more complex, high molecular weight PAHs. (*Knize et al*., 1999; *Nie et al.*, 2018b). Furthermore, PAHs can also be produced by pouring fat over a heat source. Fat drips from foods onto heat sources produce incomplete combustion of fat and the emission of light PAHs. These PAHs then migrate via smoke to the foods, where they are adsorbed (*Zhu et al*., 2022). *Chen and Chen* (2001) identified fatty acids as being able to form hydroperoxides on oxidation, which produce cyclic compounds, such as cyclohexene, by intramolecular cyclization. These ringed compounds can further stack to give benzene rings and eventually grow into PAHs by the Diels-Alder mechanism. The combined action of these three formation pathways under the grilling process result in the occurrence of high concentrations of PAHs in grilled food, which need to be considered to ensure the protection of human health.

3. Factors influencing PAH levels during meat grilling

The development of polycyclic aromatic hydrocarbons (PAHs) in grilled foods can be affected by multiple variables (*Du et al*., 2025), including the type of food being cooked (*Lee et al.*, 2016; *Sahin et al*., 2020), the nature of the fuel used (Kim et al., 2021), the time of the grilling process (*Kao et al*., 2014), as well as the temperature and intensity of heat exposure during grilling (*Onopiuk et al*., 2021; *Sumer and Oz*, 2023). The composition of fuel, and the level of direct contact between food and the flame, are instrumental in determining the levels of PAHs in grilled foods. Several studies have proven that charcoal grilling produces much higher PAH levels compared to gas grilling (*Alomirah et al*., 2011; *Anjum et al*., 2019; *Chung et al*., 2021; *Farhadian et al.*, 2010a; *Lateef and Walker*, 2015). This disparity is mostly explained by the emissions produced during charcoal combustion, which significantly contribute to PAH formation (*Chaemsai et al*., 2016; *Iko Afé et al*., 2020). Furthermore, the type of charcoal used, i.e., white, black, or extruded, affects the PAH content, with extruded charcoal generating the highest concentrations (*Kim et al*., 2021). The grilling method, whether direct or indirect, plays a crucial role

in PAH levels. *Sumer and Oz* (2023) observed that direct grilling yields considerably greater PAH concentrations than indirect grilling. Supporting this, *Lee et al.* (2016) and *Anjum et al*. (2019) demonstrated that cooking with direct charcoal fire can increase benzo[a]pyrene (BaP) levels by five times or more compared to indirect techniques. This significant increase is attributed to factors such as the proximity of food to the heat source, elevated temperatures, and smoke and tar production from fat dripping onto the heat source, all promoting PAH formation (*Hamidi et al*., 2022; *Lee et al*., 2016). Temperature, cooking time, and fat content play key roles in PAH formation during grilling. Longer cooking times generally result in higher PAH accumulation due to enhanced pyrolytic and oxidative reactions; however, temperature exerts a stronger influence on PAH synthesis (*Min et al*., 2018; *Rose et al*., 2015). Indirect grilling at moderate temperatures tends to produce lower PAH levels, whereas direct grilling over open flames or charcoal at high temperatures generates substantially more PAHs. This increase is primarily due to incomplete combustion and pyrolysis of fat drippings (*Liu et al*., 2019; *Onopiuk et al*., 2021; *Singh et al*., 2023). Elevated temperatures also facilitate the transformation of lighter PAHs into more complex and toxic compounds (*Wang et al*., 2017; *Zhang et al*., 2021). Fat content in meat greatly influences PAH levels; higher fat content promotes dripping and pyrolysis on heated surfaces, increasing PAH formation (*Babaoglu et al*., 2017; *Hamidi et al*., 2022; *Perelló et al*., 2008). Studies confirm that fattier cuts accumulate more PAHs than lean cuts under identical grilling conditions (*Dost and İdeli*, 2012; *Lee et al*., 2016). Substituting fatty meats with leaner cuts or plant-based alternatives could reduce dietary PAH exposure, although cultural habits likely would impact the acceptance of such changes (*Wang et al*., 2022).

4. Ways to reduce PAH formation in grilled meat

A significant amount of research has looked into different ways to reduce the formation of polycyclic aromatic hydrocarbons (PAHs) in grilled meats. Marination and changes to traditional grilling methods stand out as the most effective approaches (*Du et al*., 2025; *Hasyimah et al*., 2022; *Mehl et al*., 2019). Marinating meat before grilling is seen as a straightforward yet powerful way to lower PAH levels under regular cooking conditions. This effectiveness largely comes from the antioxidants in the marinade that neutralize free radicals produced during cooking. These radicals are key players in PAH formation (*Arun et al*., 2023; *Esfahani Mehr et al.*, 2019; *Kao et al.*, 2014; *Nor Hasyimah et al*., 2020). Several studies have shown the antioxidant power of various marinades, confirming their role in blocking PAHs (*Viegas et al*., 2012; *Wang et al*., 2017). However, marination can have downsides, as foods in marinades or sauces can char more easily. This outcome can ironically increase PAH levels on the food surface (*Ahmad Kamal et al*., 2018). Therefore, careful control of grilling conditions is vital to achieve a balance between lowering PAHs and avoiding excessive charring. Moreover, the detailed ways in which antioxidants interact with free radicals during cooking and their overall effect on PAH levels still need more exploration (*Zhang et al*., 2021).

Besides marination, changing grilling methods can significantly cut down PAH exposure. Pre-treatments like steaming or microwave heating before grilling reduce PAH levels by decreasing cooking time and limiting direct contact with smoke and pyrolysis products (*Farhadian et al*., 2010b). Additionally, wrapping meat in materials like aluminium foil or banana leaves can prevent PAH deposition by acting as a physical barrier. Notably, banana leaves work better than aluminium foil (*Farhadian et al*., 2010b; *Gorji et al.*, 2016). Another important factor in PAH formation is the contact of fat drippings with the heat source, which leads to pyrolysis and further PAH generation. Keeping fat drippings away from flames or hot surfaces significantly lowers PAH formation (*Duedahl-Olesen and Ionas*, 2022; *Farhadian et al*., 2010b; *Lee et al.*, 2016; *Min et al*., 2018). In summary, these findings show that using antioxidant-rich marinades, controlled grilling techniques, pre-treatment methods, and physical barriers can work together to lower PAH contamination in grilled meats. This strategy can help reduce dietary exposure and related health risks.

5. Health risks

Polycyclic aromatic hydrocarbons (PAHs) comprise over 600 compounds, with benzo[a]pyrene (BaP) being the most studied and classified by IARC as carcinogenic to humans (Group 1). Others, such as benzo[b]fluoranthene (BbF), benzo[a] anthracene (BaA), and chrysene (CHR), are classified as possibly carcinogenic to humans (Group 2B) based on limited evidence (*International Agency*

for Research on Cancer, 2010). PAHs occur in complex mixtures with potential synergistic toxicity and, unlike spoilage markers, are undetectable by smell, taste, or appearance, increasing unintentional intake (*Sampaio et al*., 2021). Due to their lipophilicity, PAHs accumulate in high-fat foods (beef, poultry, fish) and are absorbed via dietary lipids, particularly BaP, which travels systemically bound to lipoproteins, accumulating in the liver and intestinal mucosa (*Mallah et al*., 2022; *Sampaio et al*., 2021). Once inside cells, PAHs undergo bioactivation via CYP1A1 into reactive epoxides that bind DNA and proteins, initiating carcinogenesis (*Afé et al*., 2021). This mechanism is supported by findings of DNA adducts in colorectal tumours of individuals with high meat intake (*Cheng et al*., 2021). The gut microbiota also influences PAH toxicity by modulating enterohepatic recycling, hepatic enzyme expression, and local PAH biotransformation, while microbial dysbiosis could act synergistically with PAHs and other meat-derived carcinogens to promote mutagenesis and oncogene activation (*Abu-Ghazaleh et al*., 2020). Additionally, microbial metabolism can generate estrogenic PAH metabolites, adding potential endocrine-disrupting effects (*Afé et al*., 2021). An early study from a Slovenian-populated region of Hungary reported unusually high stomach cancer incidence in a population consuming home-smoked meats prepared with softwood, a practice linked to elevated PAH formation (*Fritz and Soos*, 1980).

Contemporary epidemiological studies and meta-analyses consistently demonstrate a strong association between high intake of red and processed meats, major dietary sources of PAHs, and increased cancer risk. In the NIH-AARP cohort, individuals with the highest red meat intake had a 20-60% higher risk of colorectal, liver, lung, and oesophageal cancers, while high processed meat intake was associated with 20% greater colorectal and 16% greater lung cancer risk (*Cross et al*., 2007). *Chan et al*. (2011) confirmed a dose-response relationship: each 100 g/day of red meat raised colorectal cancer risk by 17%, and 50 g/day of processed meat raised this risk by 18%, up to a plateau. Additional carcinogens in processed meats, including nitrosyl-heme and heterocyclic amines, likely act synergistically with PAHs. A meta-analysis of 148 studies (*Farvid et al*., 2021) extended these findings to multiple cancers, including breast, colon, lung, and liver. However, the E3N French cohort showed no clear link between dietary PAH4 intake and overall mortality, except for increased lung cancer mortality in current smokers, suggesting additive effects of inhaled and ingested PAHs. Beyond this, PAH exposure has been associated with poorer outcomes in breast cancer survivors and may contribute to lung cancer in never-smokers via inhalation of cooking-related emissions (*LoPiccolo et al*., 2024). Occupational exposure to PAHs, particularly in grilling environments, also presents a significant health concern. Restaurant grill workers experience markedly elevated internal PAH burdens, with *Oliveira et al.,* (2020) reporting a ninefold increase in total urinary hydroxylated PAH metabolites (OHPAHs) during workdays. Grilling over charcoal briquettes emits extremely high PAH levels, with all solid fuel scenarios exceeding the incremental lifetime cancer risk (ILCR) threshold of 10^{-4}, indicating unacceptable inhalation-related risks (*Badyda et al.,* 2022). These exposures correspond to measurable genetic damage; *Cao et al.,* (2021) found a 45% increase in PIG-A gene mutation frequency among barbecue workers, with strong correlations between urinary PAH levels and biomarkers of genotoxicity. These findings confirm that traditional grilling poses not only dietary but also inhalation-based carcinogenic risks, especially in occupational settings. Health risk assessments should consider both exposure routes and promote ventilation, exposure limits, and safer cooking practices.

6. Conclusion

Grilled meat is an important part of Serbian culture and is widely consumed. However, we still do not fully understand the risks associated with exposure to harmful PAHs. Several factors contribute to the formation of PAHs, including the grilling method, type of fuel, fat content, and temperature. This highlights the need for strategies that are tailored to local practices. Using antioxidant-rich marinades, improving grilling techniques, and educating the public can help lower PAH intake while preserving culinary traditions. There is increasing evidence that links dietary PAHs to negative health effects, but several challenges make it hard to interpret these findings. Oral intake is just one way people can be exposed to PAHs, as inhalation and skin contact also play a role. Observational studies, different influencing factors, individual genetic differences, and the presence of other carcinogens in processed meats make it difficult to pinpoint the exact impact of PAHs. Current biomonitoring tools are not able to

separate the different exposure routes. This shows the need for thorough long-term research and standardized assessment methods to better grasp how dietary PAHs affect health.

Disclosure Statement: No potential conflict of interest was reported by the authors.

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