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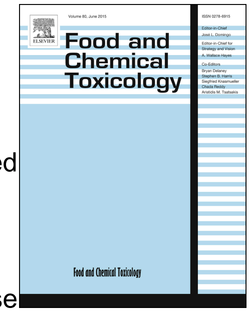

Insight about methods used for polycyclic aromatic hydrocarbons reduction in smoked or grilled fishery and meat products for future re-engineering: A systematic review

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Insight about methods used for polycyclic aromatic hydrocarbons reduction in smoked or grilled fishery and meat products for future re-engineering: a systematic review

Ogouyôm Herbert Iko Afé[ab], Caroline Douny[a], Yénoukounmè Euloge Kpoclou[b], Ahmed Igout[c], Jacques Mahillon[d], Victor Anihouvi[b], Djidjoho Joseph Hounhouigan[b] and Marie-Louise Scippo[a*]

[a]Laboratory of Food Analysis, Department of Food Sciences, Faculty of Veterinary Medicine, Fundamental and Applied Research for Animals & Health (FARAH), Veterinary Public Health, University of Liège, bât. B43bis, 10 Avenue de Cureghem, Sart-Tilman, B-4000 Liège, Belgium

[b]Laboratory of Food Sciences, School of Nutrition, Food Science and Technology, Faculty of Agronomic Sciences, University of Abomey-Calavi, 03 P.O Box 2819, Cotonou, Benin

[c]Department of biomedical and preclinic Sciences, Faculty of Medicine, University of Liège, Bât. B23, 13 Avenue Hippocrate 13, Sart-Tilman, B-4000 Liège, Belgium

[d]Laboratory of Food and Environmental Microbiology, Faculty of Bioscience Engineering, UCLouvain, Croix du Sud, 2 - L7.05.12, B-1348 Louvain-la-Neuve, Belgium

*Corresponding author. mlscippo@uliege.be

Abstract

This paper presents methods of reduction of polycyclic aromatic hydrocarbons (PAHs) in grilled or smoked meat and fishery products. Using keywords such as "smoking", "grilling", "processing", "roasting", "barbecue", "curing", "reduction", "decrease", "polycyclic aromatic hydrocarbon", "benzo(a)pyrene", "removal", 1191 references were collected from databases. After sorting, only 37 appeared to be relevant to the topic of the review. These 37 papers were coded with one or two keywords representing methods of PAHs reduction using R-based

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Qualitative Data Analysis library. The results showed that PAHs reduction strategies can be applied either before (or during) grilling or smoking (barrier methods) or after grilling or smoking (removal methods). Before grilling or smoking, use of marinade, preheating of products, appropriate fuel (poor in lignin), filter, collection system of juice and fat (to avoid them dripping into embers) are the main strategies which can be applied. After grilling or smoking, the methods consist of washing the surface of smoked or grilled products with hot water (60 °C) or storing smoked products packed into low density or high density polyethylene. A flowchart regrouping methods which can be used individually or in combination for PAHs reduction in smoked meat and fishery products is suggested.

Keywords: systematic review, benzo(a)pyrene, PAHs removal, food safety

1. Introduction

Polycyclic aromatic hydrocarbons (PAHs) are environmental pollutants which are also found in processed food after heat treatment such as roasting or grilling and smoking (SCF, 2002; WHO, 2006). Since PAHs are recognized to be carcinogenic to humans, several studies have been carried out to investigate its presence in food and feed (Yebra-Pimentel et al., 2012; Essumang et al., 2013; Yebra-Pimentel et al., 2013; Fasano et al., 2016; Rozentale et al., 2018; Ingenbleek et al., 2019). Scientific Committee on Food (SCF) of European commission selected, based on their genotoxicity and carcinogenicity, sixteen PAHs as priority to be investigated in food (SCF, 2002). According to the European Food Safety Authority (EFSA), four polycyclic aromatic hydrocarbons [PAH4: benzo(a)pyrene (BaP), benz(a)anthracene (BaA), benzo(b)fluoranthene (BbF) and chrysene (CHR)] are the suitable indicators to be used for PAHs occurrence and toxicity in food (EFSA, 2008). Among these PAH4, BaP was classified in group 1 (carcinogenic to human) and the three others were classified in group 2B (possibly carcinogenic to humans) by the International Agency for Research on Cancer (IARC) (WHO/IARC, 2012). In 2006, European Commission set maximum limits of 5 µg/kg

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and 30 µg/kg for BaP and sum of PAH4, respectively, in smoked meat and fish. These limits were then revised and the new limits are, since September 1st, 2014, 2 µg/kg and 12 µg/kg for BaP and sum of PAH4, respectively, in smoked meat and fish (EC regulation No. 1881/2006). Traditional methods of grilling and smoking lead to PAHs contamination of processed food, including smoked shrimp and fish (Akpambang et al., 2009; Kpoclou et al., 2014; Ingenbleek et al., 2019) and grilled or smoked meat (Essumang et al., 2012; Viegas et al., 2012; Duedahl-Olesen et al., 2015). During traditional food smoking, the product is laid on mesh tray or even hung on support directly above burning wood or charcoal (Berkel et al., 2004; Kpoclou et al., 2014; Assogba et al., 2019). Also, various fuels (like coconut shell and husk), wood species (such as *Acacia auriculiformis*; *Mangifera indica*) and smoking equipments (like Chorkor and barrel kilns) can be used during traditional smoking of fishery products (Essumang et al., 2013; Kpoclou et al.,2014; Assogba et al., 2019). These kinds of fuels were reported to be factors enhancing PAHs formation (Codex Alimentarius, 2009; Kpoclou et al., 2014). In shrimp traditionally smoked using acacia wood and a Chorkor kiln in Benin, Kpoclou et al. (2014) reported very high levels of BaP and PAH4 (around 100 µg/kg and 400 µg/kg for BaP and PAH4, respectively), far above the EU maximum limits. Elevated levels of BaP were also reported in commercial samples of smoked fish collected from Benin and Nigeria markets, exceeding 15 times (Akpambang et al., 2009) and 39 times (Ingenbleek et al., 2019) the EU threshold of 2 µg/kg. The presence of PAHs in grilled or smoked meat and fishery products was also reported by several authors (Perelló et al., 2009; Martorell et al., 2012; Viegas et al., 2012; Fasano et al., 2016; Rey-Salgueiro et al., 2017; Rozentale et al., 2018; Ingenbleek et al., 2019; Mastanjević et al., 2020). Because of the high toxicity of these compounds (including genotoxicity and carcinogenicity), several studies were carried out on population consuming such PAHs contaminated food, including meat and fishery products (Llobet et al., 2006; EFSA, 2008; Martí-Cid et al., 2008; Domingo and Nadal, 2015; Iko Afé et al., 2020).

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The formation of polycyclic aromatic hydrocarbons in food could be influenced by several factors. Codex Alimentarius (2009) enumerated ten of these factors which are: fat content of the food and what happens to it during processing; fuel (woods and other plant material and others); smoking method (direct or indirect); smoke generation process in relation to the temperature of pyrolysis and to airflow in the case of a smoke generator (friction, smouldering, thermostated plates); distance between the food and the heat source; position of the food in relation to the heat source; duration of smoking; temperature during smoking; design of the smoking chamber and the equipment used for smoke/air mixture (which influences the smoke density in the smoking chamber); cleanliness and maintenance of equipment.

Several studies (Roseiro et al., 2011; Skaljac et al., 2014; Skaljac et al., 2018) reported that modifying traditional smoking techniques enable to reduce PAHs formation. Among innovation associated to smoking equipment, we can list the presence of a ventilator (to ensure homogeneity of heat or to maintain temperature in smoking chamber), of trolleys (for hanging product), or of devices to collect fat and prevent it from falling into embers (Stumpe-Viksna et al., 2008; Roseiro et al., 2011; Essumang et al., 2014; Lee et al., 2016; Skaljac et al., 2018, Bomfeh et al., 2019). The use of indirect smoking technique and the presence of a filter have also been recorded (Codex Alimentarius, 2009; Bomfeh et al., 2019).

This literature review presents several methods used to reduce PAHs in smoked or grilled meat and fishery products for future re-engineering of traditional methods.

2. Methodology

2.1. Inclusion criteria

Only original papers published after 2000, based on reduction of polycyclic aromatic hydrocarbons in meat and fishery products, were taken into consideration.

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2.2. Search strategy

Scientific papers were searched on online databases such as AGORA (Access to Global Online Research in Agriculture), Science Direct and Google Scholar on July 2018, using specific terms individually or in combination using Boolean tools (or, and, not). These terms were "smoking", "grilling", "processing", "roasting", "barbecue", "curing", "reduction", "decrease", "polycyclic aromatic hydrocarbon", "benzo(a)pyrene", "removal". All references collected were recorded in an excel file and duplicate references were removed. A selection of relevant references related to the topic of interest was performed based first on the titles, secondly on the abstracts and finally on the full text of the paper.

2.3. Software used

Microsoft excel 2013 was used to record references for duplicate removal and for graphic realisation. EndNote software (version X3) was used to export references from web and manage them into a database. After assigning one or two keywords to selected papers, which expressed methods of PAHs reduction, the package R-based Qualitative Data Analysis (RQDA) was used from R Studio (Version 1.1.456, 2018) for qualitative analysis. All keywords were gathered in different clusters for plot construction.

3. Results and discussion

3.1. Selection of relevant papers

A total of 1191 papers were found using the keywords mentioned above, and after duplicate removal, title, abstract and full text screening, only 37 were selected to write this review (Figure 1). The geographical location of the studies of these 37 papers showed that the PAH reduction in grilled or smoked meat or fish is a worldwide concern. Among the 37 publications, 18 were from European countries and 19 were conducted in both Africa and Asia, two continents regrouping developing and emerging countries in which grilling or smoking processing is still traditionally carried out.

3.2. Network analysis of the 37 selected publications

In figure 2, the methods of PAHs reduction are represented by nodes connected among them by arrows forming a network. This network is composed of 11 methods of PAHs reduction divided in two groups called clusters. The first cluster includes 9 methods of PAHs reduction applicable before or during processing while the second cluster includes 3 methods of PAHs reduction applicable after processing (packaging of end product, use of lactic acid bacteria and washing of contaminated product with hot water), among which the use of lactic acid bacteria is applicable either before or after processing.

3.3. Reduction strategies of PAHs applicable before and during grilling or smoking

3.3.1. Type of fuel used

Several authors reported that the use of certain types of woods to generate smoke during grilling or smoking may lead to the production of more PAHs. It was also reported that fuel containing high amount of lignin produces larger amounts of PAHs during its burning (Codex Alimentarius, 2009). Moreover, soft wood contains more lignin than hard wood (Essumang et al., 2013). Table 1 presents the lignin content of some tree species. Two plant trees have less than 10% of lignin (*Sesbania sesban* and *Eucalyptus camaldulensis*), ten plant trees have lignin content between 10% and less than 20% and the three others have lignin content above 20% (Table 1). Species such as *Sesbania sesban* (6.7% lignin), *Eucalyptus camaldulensis* (7.9% lignin), *Azadirachta indica* (9.7% to 13.2% lignin), or *Mangifera indica (10.4% lignin)* could potentially produce lower amounts of PAHs when they are used for grilling or smoking. According to Kpoclou et al. (2014), acacia wood (*Acacia auriculiformis*) produced higher amounts of PAHs (BaP and sum of PAH4) than mango tree wood (*Mangifera indica*) during smoking of shrimp in both Chorkor and barrel kilns. PAHs levels (wet weight) recorded in shrimp smoked in Chorkor were 107 µg/kg (BaP) and 394 µg/kg (sum of PAH4) when acacia wood was used (Table 2a) and 67 µg/kg and 258 µg/kg for BaP and sum of PAH4, respectively, when mango tree was used (Kpoclou et al., 2014).

Essumang et al. (2013) reported that the use of sugarcane bagasse for fish smoking enables to reduce the BaP and PAH4 levels in smoked fish (mackerel, sardine, tuna) compared to acacia wood and mangroves (Table 2a).

Similar studies conducted by Stumpe-Vıksna et al. (2008) also tested several species of woods (apple, alder, alder + juniper, spruce, maple, hazel, plum, aspen, bird-cherry, rowantree and also charcoal) for pork smoking. The PAHs concentrations in smoked pork ranged between 6 and 35 µg/kg for BaP (Table 2a) and between 48 and 471 µg/kg for the sum of 15 PAHs (Table 2a) (Stumpe-Vıksna et al., 2008). The lowest BaP concentration recorded in the smoked pork were 6 µg/kg, 9 µg/kg and 9 µg/kg for apple, maple and alder respectively (Stumpe-Vıksna et al., 2008). In the same way, Duedahl-Olesen et al. (2010) explored the use of alder for fish smoking and concluded that it resulted in the production of high amounts of PAHs comparatively to the use of beech wood (data not shown).

Other studies carried out about wood species used in industrial smoking process were reported by Hitzel et al. (2013) and Malarut and Vangnai (2018). Hitzel et al. (2013) tested beech, oak, spruce, poplar, alder, hickory as well as mixed woods with addition of spices (Table 2b). These authors found out that poplar wood could be used to limit PAHs formation (Table 2b). Malarut and Vangnai (2018) reported BaP and PAH4 concentrations ranging between 0.4 and 0.5 µg/kg; and between 1.1 and 1.5 µg/kg (Table 2b) respectively, in sausage smoked using beech, neem (*Azadirachta indica*), copper pod (*Cassia siamea*), earleaf acacia (*Acacia auriculiformis*) and eucalyptus (*Eucalyptus camaldulensis*). Also, in this study, the PAH levels recorded in sausages smoked using these five wood types were below the EU maximum limits of 2 µg/kg and 12 µg/kg, for BaP and sum of PAH4 respectively. These low PAH levels reported by Hitzel et al. (2013) and Malarut and Vangnai (2018) using different

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woods seem more related to the industrial smoking technique used than to the wood species used.

3.3.2. Improvement of process during meat or fish grilling or smoking and effect on PAHs reduction

Use of casing. Gomes et al. (2013) and Ledesma et al. (2015) experimented the use of casing as a barrier against PAHs deposition and to prevent pyrolysis of melt fat. The use of hog or collagen casing resulted in significant reduction of PAHs formation during Portuguese "*chouriço*" (a dry-cured fermented sausage) production (Gomes et al., 2013) (Table 3a). In the same way, Ledesma et al. (2015) also found low levels of BaP when "*chorizo*" (Spanish smoked meat) was stuffed into natural casing (from pig intestine) or into collagen casing (Table 3a). The use of different types of casing enabled to reach levels of BaP and PAH4 below the EU maximal limits of 2 µg/kg and 12 µg/kg(Table 3a).

Treatment of fuel before smoking (data not shown). Other technique to control formation of PAHs is to apply physical or chemical treatments to the fuel before its use. Chaemsai et al. (2016) experimented the use of pre-heated (650°C) mangrove charcoal. None of individual PAH4 were detected in samples of smoke generated from mangrove charcoal burnt in a furnace. The mangrove charcoal was produced according to three carbonisation temperatures (500, 750 and 1000°C) and pre-heated at 650°C for 5 minutes, 20 minutes and 5 hours before their use (Chaemsai et al., 2016). Chaemsai et al. (2016) suggested that for PAHs reduction, it is necessary to let charcoal fully glow before starting grilling. In the same way, Lee et al. (2016) suggested that for charcoal-grilling, meat should be laid on tray 12 minutes after flame was generated. With the use of this strategy associated to the prevention of meat juice dripping into embers, Lee et al (2016) showed reduction of the sum of PAH4 of 89% (from 21.8 to 2.4 µg/kg) in grilled meat.

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Use of a filter. Essumang et al. (2014) showed that the use of charcoal filters (activated or not) in modified traditional kilns enabled to decrease PAHs amounts (compared to controls without filters) in fish smoked using acacia, for 4h (Table 3a) or sugarcane bagasse and mangroves (data not shown). All samples of fish smoked using these charcoal filters were compliant with EU regulation regarding BaP concentration. Parker et al. (2017) also developed filters composed of zeolite, which, when they were pre-treated before use allowed to reduce PAHs deposit on smoked food (data not shown). In the same way, Babić et al. (2018) also reported very low concentration of PAH in smoked carp when zeolite and other filters (gravel or granular activated carbon) were used during smoking (Table 3a). Activated carbon has been previously used to eliminate PAHs from fish oil samples using adsorbent extraction as decontamination treatment (Yebra-Pimentel et al., 2014).

Use of wrapping technique. Another way to decrease PAHs deposition on grilled meat is to create a barrier between the products and the smoke. According to Farhadian et al. (2011), when meat was wrapped in aluminium foil or banana leaves, the BaP level in grilled meat was very low (Table 3a), and below the EU maximal limit of 2 µg/kg. Similarly, Eldaly et al. (2016a), also observed the same low BaP levels (Table 3a) when beef and mutton were wrapped in aluminium foil before charcoal grilling compared to control without wrapping.

Preheating before smoking. In the study of Farhadian et al. (2011), BaP was undetectable (below 0.03 µg/kg) in grilled beef or chicken when marinated meat was preheated in microwave (180 °C; 40-60 seconds) or steam preheated (100 °C; 2-4 minutes) before grilling (Table 3b).

Use of non-conventional apparatus. Recently, Oz and Yuzer (2016) investigated PAHs content in beef steak when it was cooked on wire or stone barbecue. PAHs concentration was low in all barbecue samples no matter the cooking type in term of BaP (between undetectable (<0.07 µg/kg) and 0.3 µg/kg) and sum of PAH4 (between undetectable and 1.3 µg/kg) (Table

3b). In addition, Park et al. (2017) also reported that the use of infrared, electric grill or grill pan to grill pork belly lead to undetectable BaP levels (<0.05 µg/kg) (Table 3b).

Cold smoking, use of liquid smoke and other smoke production methods. Another way of PAHs reduction is to use liquid smoke for fish flavouring or to perform cold smoking which requires low temperature (18-25°C) (Codex Alimentarius, 2009). According to Hattula et al. (2001), the use of liquid smoke flavouring as an alternative to traditional flue gas smoking to smoke trout fillet (*Oncorhynchus mykiss*) enabled to reduce PAHs contamination of the final product (data not shown). To apply this method, fish was firstly soaked into brine solution (210 g of salt per litre), then cold smoked by dipping them 10-120 seconds in a water solution containing 10 to 12.5% of liquid smoke. In the same way, Hitzel et al. (2012) showed very low concentrations of BaP (0.3 µg/kg) and sum of PAH4 (2.5 µg/kg) in dry-smoked fermented sausage after cold smoking (Table 3b). Pöhlmann et al. (2013) also explored different smoke production methods during smoked fermented sausage production, such as smouldering smoke, steam smoke, friction smoke and touch smoke. All meat samples were compliant with EU maximal limits of BaP (2 µg/kg) and PAH4 (12 µg/kg) (Table 3b).

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3.3.3. *Use of marinade to decrease PAHs*

Use of fruit juice, spices, herbs and tea. Recently, several studies highlighted the use of some fruit juice, spices, herbs and tea to restrict PAHs formation in smoked or grilled meat by soaking meat before processing (Eldaly et al., 2016b; Sinaga et al., 2016; Park et al., 2017; Wang et al., 2017; Lu et al., 2018). Marinating meat for 60 minutes in juice of *Zanthoxylum acanthopodium* resulted in a 2.6 times reduction (Table 4) of the level of BaP in charcoal-grilled duck meat (787 µg/kg for non-marinated and 295 µg/kg for marinated meat) (Sinaga et al., 2016). However, the level of BaP was still very high and far above the EU maximal limit of BaP.

Farhadian et al. (2012) also reported reduction of BaP (70%) when beef samples were soaked in different acidic marinades (lemon juice) (Table 4) with BaP levels below the EU maximal limit (2 µg/kg). The addition of oil or/and alkali to marinade (water, sugar, oyster sauce, salt, garlic powder, black pepper powder) applied to chicken before grilling resulted in an increase of sums of PAH4 and PAH16 compared to the control without marinade (Table 4) (Wongmaneepratip and Vangnai, 2017).

Use of beer and tea. Viegas et al. (2014) experimented the use of three different beers (Pilsner beer, non-alcoholic pilsner beer and black beer) to marinate pork before grilling. Only black beer resulted in levels of BaP (1.1 µg/kg) lower than 2 µg/kg in grilled pork (Table 4). Apart from beer, marinade with green tea or white tea or yellow tea also resulted in undetectable levels of BaP (Table 4) and PAH8 (PAH4 + benzo[k]fluoranthene (BkF), benzo[ghi]perylene (BgP), dibenz[a,h]anthracene (DhA), indeno[1,2,3-cd]pyrene (IcP)) (data not shown) in charcoal-grilled chicken wings (Wang et al., 2018). Other teas like Yerba mate tea or green tea used in different proportions (0.25%, 0.5% and 1%) to marinate pork belly before grilling enabled to reduce BaP levels (12.9% to 24.5% for green tea and 18.7% to 31.5% for yerba mate tea) in charcoal-grilled pork belly pork (Park et al., 2017). However, the

BaP levels recorded in marinated charcoal-grilled pork belly (Table 4) were still exceeding the EU maximal limit of 2 µg/kg.

Use of pomace and potato juice. García-Lomillo et al. (2017) showed that the use of marinade composed of red wine pomace seasoning (RWPS) before barbecue grilling beef meat leads to a significant ($p<0.05$) increase of PAHs contents, compared to the control (BaP of non-marinated barbecued beef: 0.2 µg/kg; BaP of marinated barbecued beef: 0.3 µg/kg) (Table 4) (García-Lomillo et al., 2017). The BaP levels of samples collected before and after barbecue grilling (García-Lomillo et al., 2017) were below EU maximal limit of BaP (2 µg/kg).

Use of Lactic acid bacteria (LAB). Bartkiene et al. (2017) used lactic acid bacteria (LAB) such as *Pediococcus acidilactici* (KTU05-7), *Pediococcus pentosaceus* (KTU05-9) and *Lactobacillus sakei* (KTU05-6) to decrease PAHs content in sausage by applying them before and after smoking by using sterilised potatoes juice as substrate. According to the authors, significant decrease of PAHs (BaP and sum of PAH4) in smoked sausages treated with LAB before and after smoking was recorded (Table 4).

3.4. Methods applied after grilling or smoking for PAHs removal from processed meat or fishery products

3.4.1 .Packaging system and ultraviolet (UV) application

Kuźmicz and Ciemniak (2018) reported that when smoked sprats were stored in different types of plastic bags [Polyethylene terephthalate (PET), High-density polyethylene (HDPE), Low density polyethylene (LDPE), Polypropylene (PP), Oxo-degradable (FO)], PAHs levels highly decreased and all packed samples (stored at room temperature (22 ± 2 °C) and at cooling temperature (between+4°C and +6°C)) were compliant to EU regulation (data not shown). The reduction of BaP level (below 2 µg/kg) was also reported when LDPE film was used to pack roasted duck and smoked sausage (Table 5) (Chen and Chen, 2005; Semanová et al., 2016). According to Chen and Chen (2005), packing roasted duck meat into LDPE package at 25°C enabled to reduce 73% of BaP level after 24 hours storage (Table 5). Moreover, the same authors reported that the application of UV (2-3 hours) to LDPE film also contributes to PAHs reduction (13.5%-29.2%) and among PAHs affected by this method, BaP was the most sensitive to UV (data not shown). However, limited relevant information is available about the impact of the use of UV on food safety in food industry.

3.4.2. Washing of smoked products (data not shown)

Another method of PAHs removal from smoked fish is to wash smoked fish with hot distilled water (60°C, 2-3 minutes) (Mahugija and Njale, 2018). From eight smoked samples of *Synodontis victoriae* with BaP levels ranging between 390 and 1550 µg/kg, seven showed undetectable BaP levels (<0.1 µg/kg) after hot water washing (Mahugija and Njale, 2018). However, these authors did not discuss organoleptic characteristics of washed smoked fish, as one can expect that washing smoked product will decrease its taste and aroma. Moreover, the shelf life of washed smoked fish is short and further studies should focus on storage and preservation of the washed smoked fish.

3.5. Perspective for future process re-engineering

Among the reduction methods of PAHs in smoked or grilled products, some methods (Figure 3) can be used individually or in combination to decrease PAHs levels in food. After basic cleaning operations, the raw meat, fish or shrimp can be preheated either in microwave, or steam cooked aiming to reduce the exposure time to smoke during grilling or smoking. The crucial step is the quality of fuel (charcoal or wood) to be used for smoke production. The use of dry wood having low lignin content is recommended. Smoking can be performed by using a direct or an indirect technique. In the direct technique, the smoke is generated in the same chamber in which the food is processed, contrary to the indirect process where the smoke is being developed in a chamber, separate from where the food is smoked (Codex Alimentarius, 2009). In both techniques, the smoking equipment should have a filter composed of charcoal or activated charcoal (Esumang et al., 2014) or zeolite (Parker et al., 2017; Babić et al., 2018) or luffa sponge (vegetable filter) (Ndiaye et al., 2014; Bomfeh et al., 2019). Moreover, the smoking equipment should have a fat collection system which enable to avoid fat dripping into embers during smoking or grilling. Additionally, before laying the raw material on mesh tray, the smoking equipment should firstly be heated for about 12 minutes from the moment the flames appear as suggested by Lee et al. (2016). The smoked product can eventually be washed using hot water (for immediate consumption) or directly packed in LDPE of HDPE packaging (if the legislation of the country allows the use of polyethylene). Even thought, some strategies mentioned above could not be applied for production of high quantity of food, or might affect sensory characteristics, they can be explored for a future re-engineering of traditional grilling or smoking process.

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4. Conclusions

This literature review provides relevant information for PAHs reduction or removal from grilled or smoked meat and fishery products. Marinating, preheating, use of filter and system of fat collection, wrapping of product are some techniques which can be applied before smoking or grilling while washing the end products with warm water or packing in LDPE or HDPE are some methods which can be applied after processing for PAHs reduction. The application of these techniques suggests, in some cases, additional production cost. The big challenge is the technical and financial feasibilities of these techniques in developing countries at low and medium scale.

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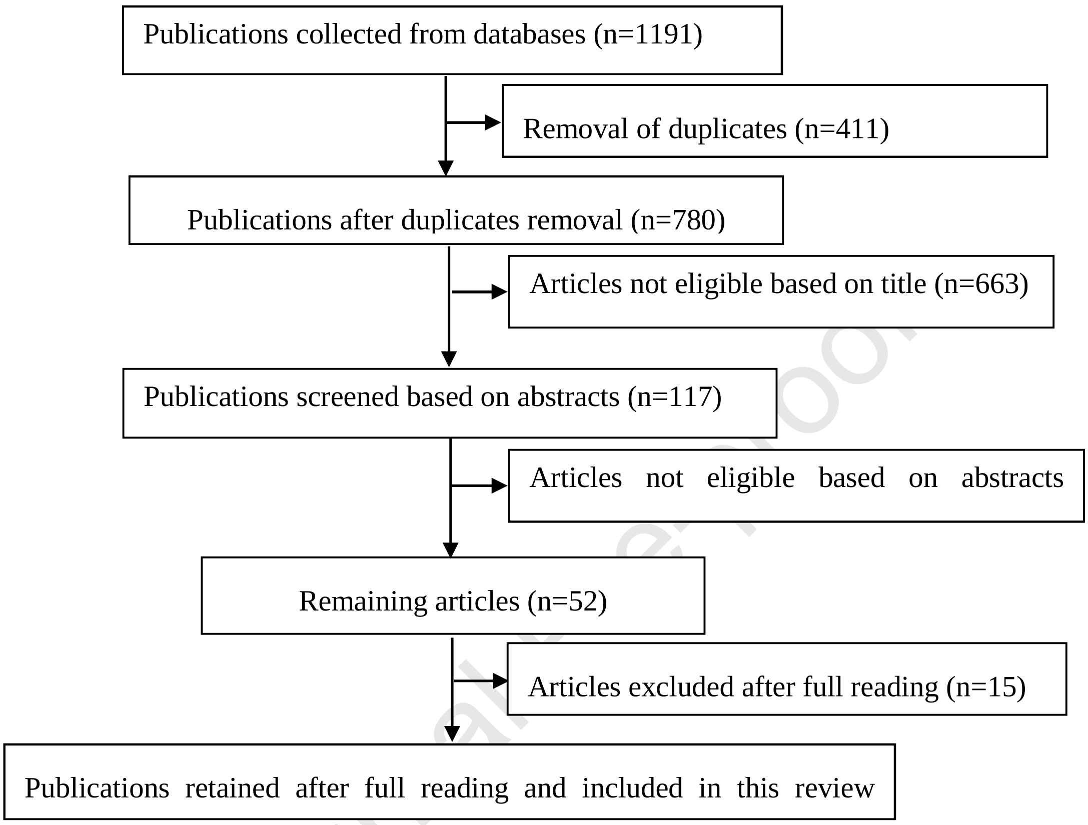

Figure 1. Flow chart of references selection to write this review. Number "n" in brackets corresponds to the number of papers selected at each stage

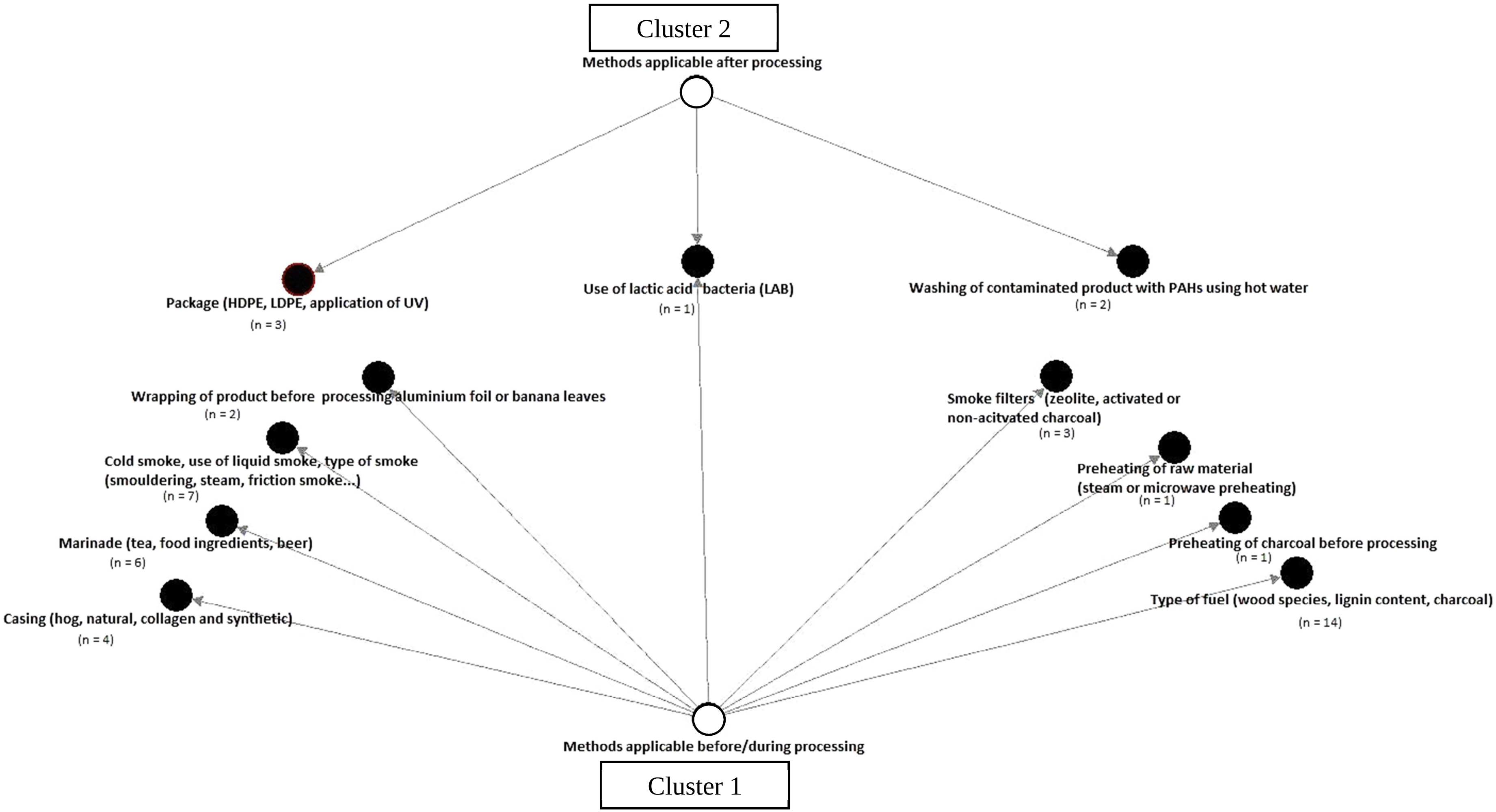

Figure 2. R-based Qualitative Data Analysis plot showing methods of PAHs reduction collected from the 37 papers selected for this review. Numbers in brackets refer to numbers of papers about the respective PAHs reduction method. HDPE: High-density polyethylene, LDPE: Low density polyethylene;

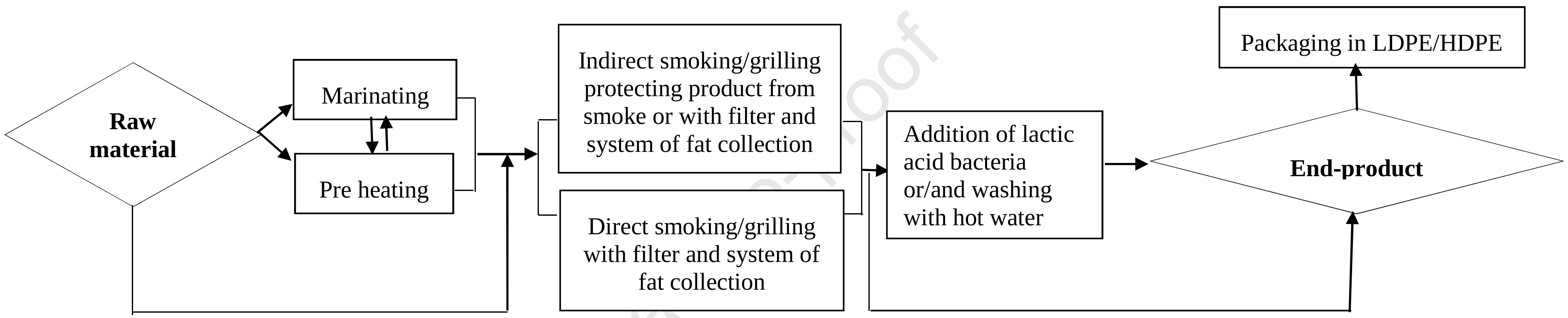

Figure 3. Flow chart showing methods of PAHs reduction applicable to meat and fishery products; LDPE: Low density polyethylene; HDPE: High-density polyethylene.

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Table 1. Lignin content of some wood species commonly used to smoke meat and fishery products

Scientific name as mentioned by the authors	Common name	Lignin content (%)	References
-	Beech	12.5	
Eucalyptus camaldulensis	Eucalyptus	7.9	Malarut and Vangnai (2018)
Cassia siamea	Copper pod	14.4	
Azadirachta indica	Neem	9.7-13.2	Malarut and Vangnai (2018)
Acacia auriculiformis	Earleaf acacia or pencil tree	13.7-14.7	Sankar Ganesh et al. (2009)
Acacia melanoxylon	-	19.7	
Acacia crassicarpa	-	21.2-23.1	Yao et al. (2010)
Acacia mangium	-	20.4-21.9	
Acacia cincinnata	-	18.7-22.2	
Cajanus cajan	Pigeon pea	14	
Calliandra calothyrus	Red calliandra	11.4	
Gliricidia sepium	Quick stick Mexican lilac	11.1	Sankar Ganesh et al. (2009)
Mangifera indica	Mango	10.4	
Flemingia macrophylla	Large leaf flemingia	19.3	
Sesbania sesban	Common sesban	6.7	

- : data not presented in the cited paper

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Table 2. PAHs levels in smoked products using different wood species or charcoal according to traditional smoking (a) and industrial smoking (b)

(a)

Type of fuel	**Smoked or grilled product**	**Smoking equipment**	**BaP (µg/kg)**	**PAH4 (µg/kg)**	**Total PAHs (µg/kg)**	**Reference and number (n) of collected samples**
Acacia auriculiformis	Shrimp	Chorkor kiln	107.0 ± 44.8	394.2 ± 165.2	-	Kpoclou et al. (2014) n = 24
Mangifera indica			67.4 ± 32.9	257.8 ± 134.1		
Acacia auriculiformis	Shrimp	Barrel kiln	91.8 ± 21.03	481.7 ± 62.6	-	
Mangifera indica			67.1 ± 20.2	280.5 ± 107.4		
Acacia	Sardine	Chorkor kiln	16.6	40.7	1143.3	Essumang et al. (2013)* n = 120
	Cigar minnows		0.5	50.7	873.2	
	Tuna		5.9	22.9	620.7	
	Mackerel		41.3	452	12801	
Sugarcane bagasse	Sardine	Chorkor kiln	1.4	17.5	670.6	Essumang et al. (2013)* n = 120
	Cigar minnows		3	57.5	547.1	
	Tuna		0.6	24.7	515.1	

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	Mackerel		1.3	169.4	942.3	
Mangroves	Sardine		1.6	43.0	859.7	Essumang et al. (2013)* n = 120
	Cigar minnows		2.9	6.8	676.2	
	Tuna		0.6	35.3	667.1	
	Mackerel		15.2	225.8	994.0	
Apple	Pork	Home-made smoking kiln	6.0	-	47.9	Stumpe-Vıksna et al. (2008) n = 30
Alder			9.4		75.3	
Alder + Juniper			20.4		192.7	
Spruce			32.3		470.9	
Maple			9.3		113	
Hazel			31		343.7	
Plum			30.6		324.7	
Aspen			35.1		307.1	
Bird-cherry			17.3		126.4	
Rowantree			20.1		183.9	
Commercial charcoal			10.01		80	

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646 **(b)**

Type of fuel	Smoked or grilled product	Smoking equipment	BaP (µg/kg)	PAH4 (µg/kg)	Total PAHs (µg/kg)	Reference and number (n) of collected samples
Beech	Frankfurter-type sausages (Mix of beef meat and pork)	A T1900 smoking chamber with a smouldering smoke generator (RZ 325), Fessmann (Winnenden, Germany),	0.7 ± 0.1	4.3 ± 0.5	10.4 ± 1.4	Hitzel et al. (2013) n = 51
Oak			0.5 ± 0.0	3.2 ± 0.3	7.3 ± 0.6	
Spruce			0.6 ± 0.1	3.3 ± 0.4	7.4 ± 0.8	
Poplar			0.4 ± 0.03	2.8 ± 0.2	6.2 ± 0.9	
Alder			0.8± 0.2	4.7 ± 0.5	10.9 ± 0.7	
Hickory			0.5 ± 0.1	2.7 ± 0.3	6.3 ± 1.1	
Beech			0.6 ± 0.1	4.8 ± 0.7	10.9 ± 0.8	
Oak			0.2 ± 0.03	2.8 ± 0.2	9.2 ± 1.6	
Spruce			0.5 ± 0.04	3.4 ± 0.2	8.1 ± 0.8	
Poplar			0.3± 0.02	2.4± 0.1	5.8 ± 0.4	
Alder			0.6 ± 0.01	4.4 ± 0.2	10.6 ± 0.3	

Hickory			0.3 ± 0.02	2.6 ± 0.03	6.9 ± 0.01	
Beech	Sausage (Pork)	Combined Chambers CS 350 (Kerres Smoke-air, Backnang, Germany)	0.5±0.03	1.5±0.04	34±2.8	Malarut and Vangnai (2018) n = 15
Azadirachta indica			0.4±0.03	1.1±0.04	34.1±0.5	
Cassia siamea			0.5±0.1	1.5±0.1	33.7±3.4	
Acacia auriculiformis			0.4±0.01	1.2±0.2	24.4±3.6	
Eucalyptus camaldulensis			0.4±0.1	1.3±0.2	33.3±0.4	

*: data of this author were presented in dry weight, - : data not presented in the cited paper; BaP : benzo(a)pyrene; PAH4: benzo(a)pyrene, benz(a)anthracene, benzo(b)fluoranthene and chrysene; Total PAH: total polycyclic aromatic hydrocarbons analysed in the cited paper.

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Table 3. PAHs levels in grilled or smoked fish and meat and products (a) using of casing, filter or wrapping technique or (b) by preheating the raw material before smoking, using non-conventional apparatus or using different smoke generation methods

(a)

Use of casing, use of filter and wrapping technique	Smoked or grilled product	BaP (µg/kg)	PAH4 (µg/kg)	Total PAHs (µg/kg)	Reference and number (n) of collected samples
Use of casing					
Hog casing + indirect smoking	*Chouriço* (Pork)	0.3	6.4	-	Gomes et al. (2013) n = 32
Hog casing + direct smoking		0.3	7.3	-	
Collagen casing + indirect smoking		0.1	4.2	-	
Collagen casing + direct smoking		0.2	4.8	-	
Natural casing	*Chorizo* (Pork)	1.7 ± 0.2	-	-	Ledesma et al. (2015) n = 16
Collagen casing		<LOD	-	-	
Type of filter					
Control	Common carp fish	0.6	2.8	185.3	Babić et al. (2018) n = 44
Zeolite		<LOD (0.6)	0.9	52.4	
Gravel		<LOD	1	66.3	
Granular activated Carbon		<LOD	<LOD	54.3	

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Control	Sardine	4.3	-	688.7	
	Cigar minnow	2.5	-	632.7	
Locally activated charcoal (Soaking in phosphoric acid and heating in furnace (600 °C, 6h))	Sardine	<LOD (0.1)	-	434.1	Essumang et al. (2014)* n = 120
	Cigar minnow	0.5	-	454.8	
Commercial activated charcoal	Sardine	<LOD	-	326.9	
	Cigar minnow	<LOD	-	284.5	
Type of wrapping technique					
Wrapping in aluminium foil	Chicken and beef	<LOD (0.03)	-	-	Farhadian et al. (2011) n = 16
Wrapping in Banana leaves	Chicken	1.5 ± 0.1	-	-	
Wrapping in Banana leaves	Beef	0.5 ± 0.1	-	-	
Without wrapping	Beef	0.5 ± 0.3	-	6.83	Eldaly et al. (2016a)
Wrapping in aluminium foil	Beef	0.1 0.1	-	1.3	
Without wrapping	Mutton	0.03 ± 0.02	-	26.8	
Wrapping in aluminium foil	Mutton	<LOD	-	6.3	

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(b)

Preheating before smoking, use of non-conventional apparatus and use of different smoke generation methods	Smoked or grilled product	BaP (µg/kg)	PAH4 (µg/kg)	Total PAHs (µg/kg)	Reference and number (n) of collected samples
Preheating before smoking					
Steam preheating or microwave preheating	Marinated beef and chicken	<LOD (0.03)	-	-	Farhadian et al. (2011) n = 16
Use of non-conventional apparatus					
Barbecue with wire	beef steak	<LOD (0.07)-0.3	<LOD-0.9	-	Oz and Yuzer. (2016) n = 32
Barbecue with stone		<LOD-0.3	<LOD-1.3	-	
Infrared-ray, electric grill or grill pan	Pork belly	<LOD (0.05)	-	-	Park et al. (2017) n = 15
Use of different smoke generation methods					
Cold smoking using smouldering smoke	Mini salamis	0.3 ± 0.2	2.5 ± 0.7	5.9 ± 1.7	Hitzel et al. (2012) n = 36

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Smouldering	Frankfurter-type sausage	1.9 ± 0.7	0.3 ± 0.1	4.8 ± 1.7	Pöhlmann et al. (2013) n = 63
Steam		0.1 ± 0.1	0.9 ± 0.7	2.1 ± 1.4	
Friction		0.03 ± 0.01	0.3 ± 0.1	0.7 ± 0.2	
Touch smoke		0.1 ± 0.02	1.6 ± 0.3	3.5 ± 0.8	

*: data of this author were presented in dry weight, <LOD: below limit of detection; - : data not presented in the cited paper; BaP : benzo(a)pyrene; PAH4: benzo(a)pyrene, benz(a)anthracene, benzo(b)fluoranthene and chrysene; Total PAH: total polycyclic aromatic hydrocarbons analysed in the cited paper.

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Table 4. PAHs levels in grilled or smoked meat products marinated before processing

Product to be grilled or smoked	**Marinade ingredients**	**BaP (µg/kg)**	**PAH4 (µg/kg)**	**Total PAHs (µg/kg)**	**Reference and number (n) of collected samples**
Non-marinated kebab (beef)	-	9.2 ± 5.7	-	119.8 ± 54.2	Eldaly et al. (2016b) n = 60
Marinated kebab	Yoghurt salt, turmeric, mustard, curry powder, cardamom, vinegar and onion	<LOD	-	57.9	
Non-marinated kofta (beef)	-	26 ± 16	-	59.2 ± 16.9	
Marinated kofta	Yoghurt, salt, turmeric, mustard, curry powder, cardamom, vinegar and onion	<LOD		30.2	
Non-marinated duck meat	-	787	-	-	Sinaga et al. (2016) n = 24
Marinated duck meat	Juice of *Zanthoxylum acanthopodium*	295	-	-	
Non-marinated beef	Beef without marinating	4.5 ± 0.4	-	-	Farhadian et al. (2012) n = 112
Beef marinated with basic (B) marinade	Sugar, water, onion, turmeric, lemon grass, salt, garlic, coriander and cinnamon	1.2 ±0.04	-	-	

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Beef marinated with basic-lemon	(B)+lemon juice	1.7 ± 0.1	-	-	
Beef marinated with basic-oil-lemon	(B)+Oil+lemon juice	1.4 ± 0.2	-	-	
Beef marinated with basic-oil-Tamarind	(B)+Oil+tamarind juice	1.6 ± 0.1	-	-	
Chicken marinated with control marinade	Water, sugar, oyster sauce, salt, garlic powder, black pepper powder	<LOD	26.3 ± 3.9	190.1 ± 22.9	Wongmaneepratip and Vangnai (2017) n = 28
Chicken marinated with palm oil marinade	Control marinade (CM)+ palm oil	<LOD	140.4 ± 20.2	457.6 ± 46.9	
Chicken marinated with sunflower oil marinade	CM+Sunflower oil	<LOD	133.3 ± 26.3	376.6 ± 41.5	
Chicken marinated with acid marinade	Palm oil marinade +citric acid	<LOD	163.1 ± 13.6	534.9 ± 51.1	
Chicken marinated with base marinade	Palm oil marinade +Sodium bicarbonate	<LOD	146.3 ± 26.5	683.2 ± 119.6	
Non-marinated pork (control)	Non-marinated	2.7 ± 0.8	-	-	Viegas et al. (2014) n = 32
Pork marinated with pilsner beer (PB)	-	2.17 ± 0.8	-	-	

Pork marinated with non-alcoholic PB	-	2.0 ± 0.2	-	-	
Pork marinated with black beer	-	1.1 ± 0.1	-	-	
Chicken wing marinated with distilled water (control)	Distilled water	3.7 ± 0.6	-	-	Wang et al. (2018) n = 40
Chicken wing marinated with green tea	-	<LOD	-	-	
Chicken wing marinated with white tea	-	<LOD	-	-	
Chicken wing marinated with yellow tea	-	<LOD	-	-	
Chicken wing marinated with oolong tea	-	3.6 ± 0.5	-	-	
Chicken wing marinated with dark tea	-	3.1 ± 0.4	-	-	
Chicken wing marinated with black tea	-	3.6 ± 0.7	-	-	
Non-marinated pork belly (Control)	Non-marinated	8.0 ± 0.03	-	-	Park et al. (2017) n = 15
Pork belly marinated with	-	6.1 ± 0.1	-	-	

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green tea					
Pork belly marinated with yerba mate	-	5.5 ± 0.1	-	-	
Non-marinated beef, (Control, 0 day)	-	0.2 ± 0.04	-	9.7 ± 0.9	
Beef marinated with red wine pomace seasoning (RWPS) (0 day)	-	0.34 ± 0.05	-	16.6 ± 0.4	García-Lomillo et al. (2017) n = 32
Non-marinated beef, (Control, 9 days)	-	0.2 ± 0.03	-	16 ± 0.9	
Beef marinated with RWPS (9 days)	-	0.2 ± 0.04	-	8.8 ± 0.8	
Non-marinated pork sausage (Control)	-	0.08 ± 0.01	0.4	-	
Pork sausage marinated with potatoes juice containing *Lactobacillus sakei*	Before cold smoking	0.04 ± 0.004	0.2	-	
	After cold smoking	0.03 ± 0.002	0.3	-	Bartkiene et al. (2017) n = 27
Pork sausage marinated with potatoes juice containing *Pediococcus acidilactici*	Before cold smoking	0.04 ± 0.01	0.3	-	
	After cold smoking	0.03 ± 0.003	0.3	-	
Pork sausage marinated with	Before cold smoking	0.03 ± 0.01	0.3	-	

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potatoes juice containing *Pediococcus pentosaceus*	After cold smoking	0.04 ± 0.003	0.3	-

PAH4: benzo(a)pyrene, benz(a)anthracene, benzo(b)fluoranthene and chrysene; Total PAH: total polycyclic aromatic hydrocarbons analysed in the cited paper.

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672 **Table 5.** Benzo(a)pyrene content(μg/kg) of roasted and smoked meat products packed in low

	Time (hour)	Roasted duck skin stored at 25°C	Smoked sausage stored at 15°C
LDPE	0	3.5	3.9
	3	-	1.1
	24	0.9	-
Reference		Chen and Chen (2005)	Semanová et al. (2016)

673 density polyethylene (LDPE), according to storage time.

674 - : data not presented in the cited paper; LDPE: Low density polyethylene

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Highlights

- Evidence of PAHs reduction in meat and fishery products was proven in literature
- Preheating or wrapping of meat products or use of casing before grilling enables to reduce PAHs contamination
- The presence of filters on smoking equipment enables to decrease PAHs amount in smoked fish
- Application of marinade to meat before grilling or smoking can lead to PAHs reduction in the processed food
- To pack smoked fish or meat in low density polyethylene bags can reduce PAHs levels

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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