Review

Impact of Smoking Technology on the Quality of Food Products: Absorption of Polycyclic Aromatic Hydrocarbons (PAHs) by Food Products during Smoking

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Abstract: The food industry is striving for a sustainable development of thermal food processing. Smoking is an example of a process that has grown in popularity in recent years. There is a lack of systematic knowledge in the literature regarding this undervalued process, so the purpose of this review is to analyze the state of knowledge about the methods and technologies of smoking food products and their impact on changing the quality of essential food products. Therefore, a comprehensive review of the literature on smoking processes from the past two decades was conducted. The most essential components absorbed from smoke during smoking are polycyclic aromatic hydrocarbons (PAHs). In the present work, 24 PAHs are summarized, and the capability of 12 food products to absorb them is described. Analysis of the principal components of absorbed PAHs showed that some products from different groups exhibit a similar ability to absorb these compounds, mainly influenced by their physical properties. The pre-treatment practices of raw materials before smoking, the smoking raw materials used, and their quality parameters were characterized (along with the effects of smoking methods on selected product groups: fish, meats, and cheeses). In addition, the gap in research concerning the absorption of other components of smoke, e.g., phenols, alcohols, ketones, and aldehydes, which directly impact food quality, is indicated.

Keywords: polycyclic aromatic hydrocarbons; smoking technology; food preservation; smoke components absorption; food quality

1. Introduction

The food industry has a key role in the sustainability of the economy. Of particular importance is the thermal processing of food. These processes should be carried out in such a way as to generate the minimum possible amount of waste, reduce the consumption of energy and non-renewable raw materials, and not introduce substances harmful to human health into food products. Thermal treatment of food imparts properties that make them safe for consumption and extend their shelf life. It involves reducing the water content and inhibiting microbial growth [1]. In addition, it increases the assimilability of nutrients and improves the texture, consistency, and physicochemical properties [2]. In addition, there is a favorable change in organoleptic characteristics, i.e., taste, aroma, and appearance. There are several basic techniques of thermal processing of food: boiling, blanching, frying, stewing, baking, grilling, roasting, drying, and smoking [3,4]. To ensure the indicated factors of sustainable development, it is necessary to conduct the mentioned processes correctly.

This review focuses on the smoking process, which involves displacing water from the raw material while saturating the aroma. As a result, it reduces the activity of water
and enzymes, and the growth of microorganisms is inhibited [5]. In addition, the elevated temperature causes the chemical compounds present in the smoke (mainly phenolic derivatives, organic acids, and carbonyl compounds) to react with food ingredients, imparting flavor and aromatic properties and changing the color and texture of the product. However, smoking also causes contamination of foodstuffs with toxic and carcinogenic substances, such as PAHs, cyclic amines, and formaldehyde. Due to the harmfulness of these substances, the aim is to minimize their contribution to the product [6]. In the smoking process, it is crucial to set temperature conditions for an experimentally determined period and in suitable smoking equipment with controlled smoke levels [7].

The high content of PAHs in products is an undesirable phenomenon, as they are carcinogens and cause cardiovascular diseases. In the European Union, there are regulations about the maximum content of certain PAHs in meat and fish by legal acts (e.g., Commission Regulation (EU) No 2023/915 of 25 April 2023, Commission Implementing Regulation (EU) No 1321/2013 of 10 December 2013, Commission Regulation (EU) No 835/2011 of 19 August 2011, and European Parliament Regulation and of the Council (EC) No 2065/2003 of 10 November 2003), and this mainly applies to Benzo[a]pyrene (BaP). However, there are no regulations regarding the content of PAHs in smoked cheeses. In the cited legal acts, the maximum BaP content cannot exceed 5.0 µg/kg, while the total content of Benzo[a]pyrene (BaP), Benz[a]anthracene (BaA), Benzo[b]fluoranthene (BbF), and Chrysene (Chr) may not be greater than 30.0 µg/kg [8–11]. For the sustainable development of smoking technologies, it becomes necessary to select the technological parameters of the smoking process in such a way that the products subjected to it do not pose a threat to human health. This can be ensured, e.g., by limiting the content of PAHs in smoked products [12,13]. To make this possible, it is necessary to check how individual products subjected to smoking absorb these compounds from smoke. Only then will it be possible to manipulate technological parameters to reduce their amount.

The literature needs to have a systematization of current knowledge about the smoking process, smoking technologies, their effects on various food products, and proper conduct of the process to ensure sustainable development. Recent research has described only the profile of PAHs, the texture of products, and the impact of wood type on the product’s organoleptic characteristics. However, there needs to be more research on, e.g., the content of phenols, organic acids, ketones, and other volatile smoke compounds and their effects on the product due to their crucial role in sustainable processing. Therefore, this study aimed to analyze smoking technologies’ state of the art and their impact on commonly consumed smoked food products. The study’s results made it possible to systematize the knowledge of food processing by smoking methods and placed it in sustainability development with an indication of directions for future empirical research. Answering two formulated research questions will make it likely to achieve the adopted aim of the work.

RQ1: How do smoking methods and raw materials affect the various products smoked for sustainable development?

RQ2: How does the change in the saturation of a smoked product with polycyclic aromatic hydrocarbons absorbed from smoke correlate with its safety for consumption?

2. State of the Art

The state of the art was analyzed using over 400 scientific articles and legal acts. As a result of a thorough content selection, 126 papers describing the results of empirical research, 9 review papers, and 4 regulations of the European Union Commission were used for the study. The cited publications were selected using Scopus, Science Direct, Web of Science, and PubMed. Keywords in the databases were smoking methods, meat smoking, fish smoking, cheese smoking, absorption of polycyclic aromatic hydrocarbons, and methods of smoke production.

Based on the literature analysis, smoking technologies and their effects on the smoking product, the selection of smoking raw materials, methods of smoke production, and the impact of consuming smoking products on human health were characterized.
Twenty-four polycyclic aromatic hydrocarbons were identified: Benz[a]anthracene (BaA), Benzo[b]fluoranthene (BbF), Benzo[k]fluoranthene (BkF), Benzo[j]fluoranthene (BjF), Benzo[g,h,i]perylene (BgP), Benzo[a]pyrene (BaP), Benzo[c]fluorene (BcL), Dibenzo[a,l]pyrene (DlP), Dibenzo[a,i]pyrene (DiP), Dibenzo[a,e]pyrene (DeP), Dibenzo[a,h]pyrene (DhP), Dibenzo[a,h]anthracene (DhA), Indeno[1,2,3-c,d]pyrene (IcP), Cyclopenta[c,d]pyrene (Ccpp), 5-Methylchrysene (5MC), Chrysene (Chr), Pyrene (Pyr), Fluorene (Fle), Phenanthrene (Phe), Anthracene (Ant), Naphthalene (Nap), Fluoranthene (Fla), Acenaphthylene (Acl), and Acenaphthene (Ace). The results were statistically analyzed using Principal Components Analysis (PCA) in Statistica 13.3 software (StatSoft, Cracow, Poland).

2.1. Smoking Technologies Characteristics

The main effect of the smoking process is preserving food. It also imparts individual sensory properties (change in taste, aroma, and color) and causes changes in the product’s structure. The intensity of absorption of smoke components into the product depends primarily on the density of the smoke and the type of fuel from which it is produced [14]. This process slows down the oxidation of food components, especially fats. In addition, some of the compounds in the smoke have bacteriostatic, bactericidal, or fungicidal properties, which prolongs the suitability of food for consumption [15]. The type of wood determines the flavor, aroma, and color properties of processed food since during smoking, a coating, the so-called “crust” is produced on the surface, which is the result of the reaction of smoke components and product proteins (protein surface shear) [16]. An important aspect of smoking technology is the content of harmful compounds in the finished products, components of wood smoke gases, and their impact on human health. In addition, the proper selection of smoking technologies determines the reduction in waste and energy consumption. Compounds penetrating from the smoke into the product are mainly polycyclic unsaturated hydrocarbons (e.g., benzopyrenes, naphthalene, phenanthrene, pyrene), as well as volatile carbonyl compounds (formaldehyde, aceton, formic or acetic acid, methyl alcohol, and dioxins. The permissible content of these compounds in food products is regulated by law [17].

2.1.1. Smoking Methods

The literature most often distinguishes four basic smoking methods (Figure 1). The classification of smoking methods depends mainly on the temperature exposure of the product. The proper choice of smoking method makes it possible to reduce the content of substances penetrating from the smoke into the product, minimize the amount of smoking raw materials, and reduce energy losses.

Šimko, 2005 states that cold temperature smoking is a long-term process (1–14 days) performed in the temperature range from 15 to 25 °C and at a relative humidity of about 95% [18]. Cold smoke smoking is supposed to impart flavor to the products, significantly increase shelf life, and protect them from microorganisms [19]. The long duration of the process results in significant weight loss. It is also the least energy-intensive and waste-reducing process. The most common products smoked this way are previously untreated meats, e.g., raw hams, sausages, and fermented salami [20,21].

Smoking with warm smoke, with a temperature from 25 to 50 °C and a humidity of about 80%, takes 4 h to 2 days. This smoking method pasteurizes the raw material by heating and drying the outer layer so that the product inside retains the characteristics of the natural product. This is also a low-energy process and does not cause the product to absorb many harmful substances from the smoke. These factors are favorable for the sustainable development of smoking technologies [22].
Smoking with hot smoke at 50 to 85 °C consists of drying, proper smoking, and surface roasting. Drying removes water from the surface at 50 to 55 °C for several tens of minutes, with an entire air supply. Smoke at 45 to 60 °C is then introduced and smoked for a minimum of 100 min, causing the top layer of the product to harden and darken. During the third phase, due to temperatures ranging from 60 to 85 °C, the outer layers are cut, insulating the center from moisture in the air [23,24]. Hot smoking does not cause much loss in the weight of the product and shortens the required process time, but it is an energy-intensive process that increases the absorption of harmful substances from smoke [25].

Smoking with partial roasting proceeds similarly to smoking with hot smoke. However, in the first phase, smoke is used for 20 to 40 min, with a temperature of no less than 60 °C. The inner layers of the product reach temperatures over 85 °C, resulting in partial roasting [26]. As a result of achieving such parameters, there is a significant melting of fat and evaporation of water, which translates into increased weight loss compared to previous smoking methods [27]. This method results in the most harmful substances entering the product and is the most material- and energy-intensive.

Smoking uses a smoking extract (chemical smoking) formed by pyrolysis of wood and further condensation of vapors and fractionation of the resulting condensate (a broad spectrum of phenolic compounds, carbonyl compounds, and organic acids). The resulting condensate is filtrated to remove soot and other solid impurities [28,29]. The purpose of using a smoke preparation is to impart a smoky flavor to products without using traditional techniques for this thermal treatment, which significantly speeds up production and reduces its cost [30]. Coating products with liquid smoke (LS) involves spraying, misting, and immersion in specially adapted chambers [21,31]. Spraying consists of spraying the product with the product before heat treatment. In misting, the product is in a smoking chamber with a sprayer dispensing appropriate LS doses. Immersion involves dipping the product in a diluted solution of the smoking preparation [32–35]. Proper preparation of smoke
extracts is low-cost and eliminates the presence in food of most of the harmful substances that are naturally contained in smoke.

2.1.2. Pre-Smoking Treatment

Before smoking, products should undergo pre-treatment consisting of cleaning, parceling, curing, dripping, and drying. Proper raw material processing reduces smoking time, automatically reducing the cost of the entire process. In addition, it affects the parameters of the product during storage. The activity that most significantly impacts the product is curing (marinating). Curing involves mixing the food product with a curing mixture consisting of water and curing salt (NaCl, KNO$_2$, or NaNO$_2$), often with the addition of other agents, e.g., sugar, alcoholic beverages (wine, beer), phosphates, ascorbic acid. These additives improve the taste of the product. In addition to enhancing the taste, the curing process also affects the product’s aroma, fixing its color and slowing the oxidation process. Salt in the solution inhibits the multiplication of bacteria (pre-preservation of the product) and removes excess water [36]. The concentration of ingredients in the curing mixture and the duration of action are selected depending on the type of raw material and its properties, which the final product should have. A distinction is made between dry curing and wet curing [37,38].

Dry curing mainly involves meat and fish. It consists of adding a dry marinating mixture to a wet split product, which dissolves in the plasma, allowing the mixture’s ingredients to penetrate deep into the product [39,40].

Wet curing uses a marinating mixture with varying concentrations of curing salts and additives in two ways: temporarily immersing the product in the marinade (immersion curing) and injecting it with the curing solution [41,42].

After the curing process, the products are subjected to dripping, usually performed in a refrigerated room with a temperature of about 5°C for 24 h. In addition, after dripping, the product can be subjected to drying at a temperature of 40 to 50°C in a heated smoking chamber without access to moisture and smoke, significantly reducing the processing time [43,44].

2.1.3. Smokehouses and Smoking Chambers

Figure 2 shows a diagram of a traditional smokehouse. The design of the smoking device is selected depending on the smoking method, quantity, and type of products. It allows control and stabilization of the parameters of the smoking process so that it is possible to achieve the required shelf life of the products and the desired sensory characteristics [45]. An essential feature of any smoking chamber is smoke control, i.e., achieving such a flow of smoke through the chamber that it displaces air masses from inside [46,47].

The cold temperature smoking chamber design should allow maintaining a constant temperature inside it in the range of 15–25°C. A chilling system is required if the ambient temperature significantly exceeds the desired process temperature [48]. This system consists of a cold water circuit and a fan. The desired smoke temperature is achieved through an appropriate combustion method of the smoke-forming raw material while controlling the placement of the furnace and the combustion intensity [49].

In devices designed for high-temperature smoking, it is crucial to maintain an even flow of smoke and air mixture. Due to the significant temperature difference between the smoke and the smoking raw material, the smoke may condense, leading to dead zones inside the smokehouse, which causes uneven smoking of raw materials. To eliminate this phenomenon, smokehouses with built-in fans or more than one smoke supply are constructed [50]. A particular case of high-temperature smoking devices is smoking and scalding chambers, where smoke and hot steam are delivered inside to steam the product (quick cutting of surface layers) [51].
2.2. Smoke Characteristics

2.2.1. Selection of Smoke-Forming Raw Material

Hardwood in the form of wood chips or swarf derived from deciduous trees or a liquid smoking preparation is the most often used wood in the smoking process. Coniferous wood is not suitable for smoking due to the presence of resin, which releases highly carcinogenic compounds. In addition, hardwood has a better ratio of hemicelluloses to other components, which gives a better smoking effect [52]. The moisture content of the wood also impacts the smoking effects, which should not exceed 20% to reduce PAHs emissions, as this is a necessary factor in sustainable development [53,54]. The hardness of the wood is also essential. Hardwood, because of its high density, burns slower than softwood, which means that the volatile compounds formed are slower to oxidize. As the hardness of wood increases, the efficiency of producing smoke components relevant to the smoking process also increases. Wood should be free from fungi, putrefaction, or humus processes. Table 1 presents the basic parameters of wood hardness.

<table>
<thead>
<tr>
<th>Main parameters</th>
<th>Soft Wood</th>
<th>Hard Wood</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>[%]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cellulose</td>
<td>47.05 ± 10.69</td>
<td>49.98 ± 10.82</td>
<td>[55–60]</td>
</tr>
<tr>
<td>Hemicellulose</td>
<td>21.92 ± 12.75</td>
<td>21.16 ± 6.30</td>
<td></td>
</tr>
<tr>
<td>Lignin</td>
<td>24.90 ± 8.62</td>
<td>21.06 ± 8.04</td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td>±12.15</td>
<td>±12.03</td>
<td></td>
</tr>
<tr>
<td>Density [kg/m³]</td>
<td>±516</td>
<td>±660</td>
<td>[61–64]</td>
</tr>
<tr>
<td>Hardness [MPa]</td>
<td>±30</td>
<td>±71.5</td>
<td></td>
</tr>
</tbody>
</table>

The most used tree species are alder, beech, ash, maple, acacia, oak, and fruit trees such as cherry, apple, or walnut. The research so far shows that the organoleptic and physicochemical properties of smoking products are influenced not only by the hardness of the wood but also by the type of tree. It is mainly due to the composition of smoke, which depends on compounds unique to a given type of tree and the burning temperature of...
Table 2 presents the influence of smoke from the use of wood of different kinds of trees on the organoleptic qualities of smoking products.

### Table 2. Impact of different types of smoking materials on the organoleptic features.

<table>
<thead>
<tr>
<th>Type of Smoking Materials</th>
<th>Smoking Effect</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acacia</td>
<td>Yellow color, sweet flavor</td>
<td>[65]</td>
</tr>
<tr>
<td>Alder</td>
<td>Dark yellow to brown in color, mild flavor and aroma with no bitterness</td>
<td>[66]</td>
</tr>
<tr>
<td>Ash</td>
<td>Golden color, ripe aroma, and preferability flavor, burns quickly, and roasts product</td>
<td>[67]</td>
</tr>
<tr>
<td>Beech</td>
<td>Golden color, mild flavor, sweet aroma</td>
<td>[49,68,69]</td>
</tr>
<tr>
<td>Maple</td>
<td>Mild and slightly sweet taste, golden color</td>
<td>[66]</td>
</tr>
<tr>
<td>Oak</td>
<td>Honey flavor with a slight bitterness, brown color</td>
<td>[26,69–73]</td>
</tr>
<tr>
<td>Apple tree</td>
<td>Mild smoke with subtle fruit flavor, dark brown color</td>
<td>[55,69–73]</td>
</tr>
<tr>
<td>Cherry tree</td>
<td>Subtle fruit flavor with little bitterness, dark brown color</td>
<td>[70,72]</td>
</tr>
</tbody>
</table>

2.2.2. Smoke Production Methods

Smoke develops during controlled slow combustion of the smoking material, the course and effect of which depends on the access of atmospheric oxygen. There is thermal degradation of smoke-forming raw material with full access to oxygen and pyrolysis, i.e., combustion with limited access to oxygen. Differences in the parameters of the methods used to produce smoke make it possible to control its chemical composition, for which reason the organoleptic characteristics of the product change. The process of smoke production consists of two phases, during which the thermal decomposition of the smoke-forming raw material occurs first, followed by the oxidation of volatile compounds formed in the previous reaction. During the combustion of a smoke-forming material, the various compounds that make up this material burn as the temperature increases. Several methods of smoke production are known, but they belong into two groups: flame and flameless (Table 3). The proper choice of smoke production method reduces the release of greenhouse gases into the atmosphere.

2.3. Smoking Specificity of Selected Food

2.3.1. Smoking Fish

Smoking fish improves the nutrient absorption, preserves them, and gives them a specific taste, color, and aroma. The most popular fish species used in smoking are salmon, mackerel, trout, and herring. As a result of temperature and smoke, the fish are dried and saturated with smoke components, thanks to which they gain the desired characteristics [87]. Smoke should have low humidity and no tar. The process parameters, which are selected depending on the fish species, weight, and fat content, significantly impact the final effect of smoking fish [88]. Oily fish absorb more significant amounts of smoke compounds; therefore, their taste and aroma will be more intense than lean fish, which can be quickly dried out. The specific nature of fish allows it to be subjected to low- and high-temperature smoking [3,89].

2.3.2. Smoking Meat

The most common type of food products subjected to smoking is meat, cured in brine before smoking. The choice of smoking technology is dictated mainly by the kind of meat and the product’s desired sensory profile and durability [90]. Cold smoke is used for durable and semi-durable products, e.g., raw sausages, steamed sausages, bacon, or bacon. When smoking with warm or hot smoke, the surface of the products dries and becomes
harder. This smoking method is suitable for perishable products like pork, poultry, and beef portions [91,92].

Table 3. Smoke production methods.

<table>
<thead>
<tr>
<th>Method</th>
<th>Method Description</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Flame methods</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Smoldering</td>
<td>The crushed wood smoke-generating raw material pyrolysis at 400–80 °C. The greater degree of fragmentation, the lower the pyrolysis temperature. The smoke is not thick; smoky substances dominate it. A byproduct is the formation of tar.</td>
<td>[74,75]</td>
</tr>
<tr>
<td>Combustion</td>
<td>It takes place in an open fireplace with an entire supply of oxygen. The smoke produced is thick and dry. A flame is visible during combustion. The combustion temperature is very high (even &gt;1000 °C). The smoke mainly contains CO₂ and water steam. The share of smoking substances is negligible. The distance of the fireplace from the smoking chamber depends on the desired process temperature.</td>
<td>[76,77]</td>
</tr>
<tr>
<td><strong>Flameless methods</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frictional heating</td>
<td>The friction force generated by moving a wooden element along a metal surface converts kinetic energy into thermal energy. The temperature achieved in this way does not exceed 500 °C. The resulting smoke is not thick but has many smoky substances.</td>
<td>[78,79]</td>
</tr>
<tr>
<td>Steaming</td>
<td>Exposing wood chips to superheated steam heated to a temperature of 400 °C with a pressure of 0.13 MPa, which, together with the smoke, condenses on the product’s surface. Thanks to this, the product absorbs moisture and heat simultaneously, thus remaining juicier.</td>
<td>[20,80]</td>
</tr>
<tr>
<td>Fluidized smoke generator</td>
<td>Simultaneous occurrence of the thermal decomposition of wood chips and the oxidation of particles in the fluidized state. Air is introduced into the smoking chamber and heated to 300 °C. This method has much greater efficiency in creating dry and thick smoke with a high content of smokable substances.</td>
<td>[81,82]</td>
</tr>
<tr>
<td>Two-step</td>
<td>Smoke develops due to pyrolysis in the presence of CO₂ or N₂ and then mixed with oxygen, which causes the smoke to burn out, making it denser and richer in smokeable substances.</td>
<td>[83,84]</td>
</tr>
<tr>
<td>Smelting</td>
<td>Pyrolysis of sawdust compressed into blocks. The advantage of this method is the constant parameters of the smoke generated and the possibility of using waste from the wood industry.</td>
<td>[85,86]</td>
</tr>
</tbody>
</table>

2.3.3. Smoking Cheese

To subject the cheese to the smoking process, it must be applicable prepared and have a compact consistency. The initial processing of this smoking raw material depends on its durability and desired taste [93]. It is recommended to smoke cheeses with high fat and water content using cold or warm smoke. However, lean, dry, and compact cheeses can also be smoked hot or with partial baking [94]. The smoking time depends on the type of cheese and may last up to several hours. Smoking cheese usually takes the shortest time compared to the smoking processes of other products [95,96].

3. Results and Discussion

3.1. Characteristics of Chemical Compounds Found in Smoked Products

Due to the effects of smoke, many chemical substances accumulate in smoked products. Ledesma et al., 2016 indicate that products obtained in the smoking process contain toxic mutagenic and carcinogenic compounds, the level of which in the products depends on the selected smoking method, the smoke-producing raw material and its humidity, as well as the duration of the process [97]. Most of these compounds come from the group of polycyclic aromatic hydrocarbons (PAHs), which include over 200 substances, several of
which are extremely dangerous to human health. The research of Flores et al., 2019 showed that separating these compounds from smoke is impossible during the process. However, it should not be attempted because these compounds give the products characteristic organoleptic values [98].

Additionally, due to the lipophilic properties of PAHs, an important determinant is the fat content in the product, which increases the absorption capacity of these compounds, as proven by Chen et al., 2013 [99]. According to Zhu et al., 2012, the concentration of PAHs is influenced by long-term smoking directly at the fire. The level of PAHs in smoke increases with the increase in the pyrolysis temperature of the smoke-producing raw material, and above 500 °C, the content of the PAHs increases significantly. Most PAHs are found in the outer layers of the product [100]. Du et al., 2022 claim that conducting the smoking process using modern techniques and smoking chambers allows for strict control of the parameters and composition of the produced smoke, which may reduce the content of PAHs in products [69].

Moreover, as indicated by two independent groups of researchers (Petričević et al., 2018 and Yin et al., 2021), hundreds of other substances that do not belong to the PAHs group can be identified in smoked products [101,102]. These are mainly alcohols, aldehydes, ketones, organic acids, dioxins, heterocyclic amines or nitrosamines, esters, terpenes and phenols. The literature does not describe the determination of the content of these substances in smoked products. Therefore, for this article, it was decided to compare smoked products only by the content of PAHs (Chapter 3.2). Nevertheless, the listed substances (as indicated by Shishov et al., 2020 and Albishi et al., 2019) significantly impact the physicochemical and organoleptic characteristics of smoked products [103,104]. Research by Ledesma et al., 2015 on smoked products has shown that this product is highly resistant to oxidative processes and microbiological factors due to the preservative properties of smoke with a high content of the substances mentioned above [105]. According to Erbay et al., 2013, the dominant role in this process is the antioxidant effect of phenolic compounds in smoke. The phenols in smoked meats include guaiacol, eugenol, syringe, methyl guaiacol, cresols, and dihydrogen.

Phenols are crucial in shaping the aroma of smoked meat [106]. Ahmad et al., 2005 attribute the antiseptic effect to formaldehyde, as well as acetic acid and formic acid, which lower the pH of the product, which means that the antiseptic effect does not wear off when smoking ends [107]. However, both the studies of Duma-Kocan et al., 2020 and Cheng et al., 2023 prove that the effect obtained during smoking is caused by the synergistic effect of substances contained in the smoke, process temperature, reduced water activity and compounds contained in the product [74,108]. In the past, it was believed that sensory properties depended solely on the amount of resin compounds and tar. Research by Varlet et al., 2007 showed that the formation of a characteristic crust on the product occurs due to the Maillard reaction between smoke carbonyl compounds and product proteins [75]. Somoza et al., 2005 and Flores et al., 2019 proved that, as the temperature increases and the product dries, a dark brown color develops, which is also influenced by the deposition of solid smoke particles and the polymerization of phenols on the product’s surface. Moreover, organic acids contained in smoke fix the resulting color [98,109].

3.2. Absorption of PAHs by Popular Smoked Products

Table 4 presents the PAH profiles in popular smoked products.
<table>
<thead>
<tr>
<th>Table 4. PAH profiles in popular smoked products.</th>
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<table>
<thead>
<tr>
<th>Smoked Food</th>
<th>Polycyclic Aromatic Hydrocarbons (µg/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BaA</td>
</tr>
<tr>
<td><strong>Fish</strong></td>
<td></td>
</tr>
<tr>
<td>Salmon</td>
<td>47.66 ± 47.36</td>
</tr>
<tr>
<td>Herring</td>
<td>25.58 ± 12.41</td>
</tr>
<tr>
<td>Mackerel</td>
<td>± 19.48 ± 0.50</td>
</tr>
<tr>
<td>Rainbow trout</td>
<td>± 6.30 ± 5.11</td>
</tr>
<tr>
<td><strong>Meat</strong></td>
<td></td>
</tr>
<tr>
<td>Hove</td>
<td>± 38.28 ± 11.97</td>
</tr>
<tr>
<td>Bacon</td>
<td>4.07 ± 3.01</td>
</tr>
<tr>
<td>Sausage</td>
<td>± 7.76 ± 0.28</td>
</tr>
<tr>
<td>Poultry</td>
<td>± 0.91 ± 1.21</td>
</tr>
<tr>
<td><strong>Cheese</strong></td>
<td></td>
</tr>
<tr>
<td>Mozzarella</td>
<td>± 20.58 ± 27.82</td>
</tr>
<tr>
<td>Card</td>
<td>± 4.67 ± 2.30</td>
</tr>
<tr>
<td>Italian</td>
<td>± 1.37 ± 0.47</td>
</tr>
<tr>
<td>Hard cheese</td>
<td>± 1.14 ± 0.96</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Smoked Food</th>
<th>Polycyclic aromatic hydrocarbons (µg/kg)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cpp</td>
<td>SM C</td>
</tr>
<tr>
<td><strong>Fish</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Salmon</td>
<td>6.95 ± 9.35</td>
<td>± 0.30</td>
</tr>
<tr>
<td>Herring</td>
<td>4.68 ± 4.40</td>
<td>± 0.50</td>
</tr>
<tr>
<td>Mackerel</td>
<td>29.45 ± 34.40</td>
<td>± 0.50</td>
</tr>
<tr>
<td>Rainbow trout</td>
<td>9.65 ± 9.35</td>
<td>± 0.50</td>
</tr>
<tr>
<td><strong>Meat</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hove</td>
<td>48.31 ± 48.20</td>
<td>± 0.16</td>
</tr>
<tr>
<td>Bacon</td>
<td>17.02 ± 16.89</td>
<td>± 0.15</td>
</tr>
<tr>
<td>Sausage</td>
<td>0.50 ± 0.47</td>
<td>± 0.04</td>
</tr>
<tr>
<td>Poultry</td>
<td>± 0.15 ± 0.15</td>
<td>± 0.15</td>
</tr>
<tr>
<td><strong>Cheese</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mozzarella</td>
<td>nd</td>
<td>± 5.35</td>
</tr>
<tr>
<td>Card</td>
<td>nd</td>
<td>± 3.71</td>
</tr>
<tr>
<td>Italian</td>
<td>nd</td>
<td>± 0.89</td>
</tr>
<tr>
<td>Hard cheese</td>
<td>nd</td>
<td>± 0.50</td>
</tr>
</tbody>
</table>

nd—not detected.
The research results of various groups of scientists presented in Table 4 show that, in practice, it is complicated to maintain the legally required PAH content. In relation to the results obtained from the literature to the European Union regulations mentioned in the Introduction, we noted that only rainbow trout, sausages, and poultry fall within the normal range. In other fish and meat products, the permissible contents of the aforementioned PAHs are exceeded twice or thrice [8,10]. A common feature of these products is their high fat content, which, as mentioned earlier, increases the absorption of PAHs from smoke. Admittedly, cheeses are not covered by this directive, but in relating the PAH content of cheeses to these guidelines, we noted that only mozzarella would not meet the maximum content criteria set. This is probably due to the very loose structure of this cheese, which facilitates the absorption of PAHs.

Studies by Chen et al., 2021 and Cheng et al., 2023 indicate that the content of PAHs in products depends on the duration of the smoking process. Products that require prolonged smoking and, therefore, have a higher surface area to mass ratio absorb considerably more PAHs. The solution to this problem may be to divide the products into smaller parts, which will then be smoked (parcellation) [74,102]. The same problem was dealt with by Djinovic et al., 2008, who showed that the content of PAHs in ham, bacon, and sausages initially increased evenly during cold smoke smoking, but after three days, the content of some PAHs, e.g., Dibenzo[a,i]pyrene (DiP) and Cyclopenta[c,d]pyrene (Cpp) increased-differently, for different products. They attributed this relationship to the ratio of specific surface area to the mass of individual products [123].

The analysis of Table 4 shows that cottage cheese has by far the most remarkable ability to absorb PAHs from smoke, in which the PAH content is almost three times higher (average 2018.24 µg/kg) than in bacon (average 727.15 µg/kg). It is probably due to the loose structure of the product and its consistency, which allows for the penetration of more PAHs into the product, as indicated by studies conducted by Guillén et al., 2011 and Pluta-Kubica et al., 2020 [95,136]. In turn, the least PAHs are absorbed by Italian cheese (average 16.28 µg/kg), which does not require a long-term smoking process, as described in the study by Pagliuca et al., 2003 [137].

The content of PAHs in smoked products can be manipulated by modifying the pre-treatment of products and the technological parameters of the smoking process. At the stage of product pre-treatment, Chen et al., 2013 showed that adding sugar to the marinade can even double the content of PAHs in the products [99]. Yurchenko et al., 2005 indicate that fish marinated in oil absorb many PAHs because oil makes these compounds migrate more easily into the product [114]. Mihalca et al., 2011 claim that the degree of fragmentation of the smoke-producing raw material plays an essential role in the final content of PAHs in the product. The use of highly fragmented wood chips significantly reduces the content of PAHs [121]. Pöhlmann et al., 2012 proved that smoking at elevated temperatures contributes to increasing the content of PAHs in products and forming more complex compounds with more aromatic rings and higher molecular weight, which are much more harmful to human health [125].

Based on the analysis of the main components of the PAH content in popular smoked products (Figure 3), we found that of the PAHs selected for study, thirteen are present in all analyzed products. Among them, Fluorene (Fle), Phenanthrene (Phe), Anthracene (Ant), and Naphthalene (Nap) have the largest share. As Li et al., 2016 pointed out, these compounds have potent carcinogenic effects, meaning that smoked products should not be part of a person’s daily diet [139]. The analysis of the principal components showed that some products from different groups have similar abilities to absorb and accumulate PAHs from smoke, as indicated by tests conducted by Khalili et al., 2023 and Fasano et al., 2016 [122,132]. Based on the available data, we found that mozzarella has a similar ability to adsorb PAHs as fish (salmon, rainbow trout, herring), which is probably due to the soft structure of this type of cheese. It may be indicated by research conducted by Esposito et al., 2015 [93]. In turn, Djinovic et al., 2008 claim that the main factor causing the accumulation of PAHs is the ratio of the product’s specific surface area to its mass [123]. Ledesma et al.,
2015 claim that the high porosity of the product favors the accumulation of PAHs in meat, which is the reason for the much higher content of these compounds in bacon than in sausages or poultry [105]. However, the examined literature did not explain why the absorption of PAHs by mackerel is much higher than among the other fish discussed. Other products from different groups with similar PAH absorption capacities include sausages, poultry, Italian cheese, and hard cheese. Studies conducted by Coroian et al., 2023 and Pagulica et al., 2003 on poultry and Italian cheese show that this phenomenon is influenced by the salinity of the curing mixture [131,137].

![Figure 3](image-url)

**Figure 3.** Principal Component Analysis (PCA) of the load graph and the score plot of data from groups of popular smoked products for selected PAHs.

### 4. Conclusions

The sustainability-smoking process gives products unique organoleptic properties and should be able to reduce the absorption of harmful substances from smoke. In addition, reducing the energy intensity of the process and the smoking of raw materials is crucial for the environment. Traditional smoking methods increase many substances that negatively affect human health. Based on currently available data, cold temperature smoking results in a lower accumulation of PAHs compared to other methods. However, this is also the most time-consuming process. To improve and preserve the organoleptic qualities of the raw product and reduce the time-consuming process, the recommended form of smoking is hot smoking. An increase in the combustion temperature of the raw material significantly increases the presence of substances harmful to human health in the product. Therefore, choosing a method of generating smoke depends on reducing the combustion temperature of the raw material as much as possible by reducing the pressure in the combustion chambers, using gases supporting smoking, and/or using pressure-pressed chips of the smoke-generating raw material. An essential element is the correct preliminary processing of products. In particular, select a curing mixture with appropriate salinity and do not use marinades rich in fats. The article also shows that the use of hardwood helps reduce the content of PAHs in smoke. The ability to adsorb smoke components is mainly influenced by the physical properties of smoked products (e.g., structure, water, and fat content) and the product’s specific surface area ratio to its mass and porosity.

Smoke products contain many additional substances (phenols, aldehydes, ketones, terpenes, alcohols, acids) that are absorbed into them from the smoke. Their synergistic effect shapes the qualities of the final product. Only the content of PAHs is well described in the literature. Therefore, future empirical research should include an attempt to determine the remaining smoke components in smoked products. Additionally, research on smoked
vegetarian and vegan products is lacking. It is necessary to subject these products to the smoking process and check how the plant products absorb the smoke components. In conclusion, sustainable development of smoking technologies should involve reducing energy intensity and the consumption of raw materials. These conditions are met by the low-temperature smoking process, which is the recommended method of smoking food.

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