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REVIEW ARTICLE

Mutagenic and carcinogenic polycyclic aromatic hydrocarbons (PAHs) in food – occurrence, human health effects, and assessment methods of exposure

Mutagenne i kancerogenne wielopierścieniowe węglowodory aromatyczne (WWA) w żywności – występowanie, wpływ na zdrowie człowieka i metody oceny narażenia

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A – Koncepcja i projekt badania, B – Gromadzenie i/lub zestawianie danych, C – Analiza i interpretacja danych, D – Napisanie artykułu, E – Krytyczne zrecenzowanie artykułu, F – Zatwierdzenie ostatecznej wersji artykułu

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Abstract

Introduction. Polycyclic aromatic hydrocarbons (PAHs) are formed during incomplete combustion of organic materials. They are ubiquitous in the environment; therefore, we are in constant contact with them.

Aim. The purpose of this article is to compare different, often consumed, types of food due to their PAHs content, as well as to discuss the impact of these compounds on the human body, taking into account the methods for assessing human exposure to PAHs.

State of the knowledge. It is indicated that processing procedures and cooking methods are the main factors of PAHs contamination of food. PAHs can get into food, especially during grilling and frying. The International Agency for Research, on Cancer (IARC) has classified many of these compounds as probably carcinogenic or possibly carcinogenic and one of them, benzo[a]pyrene, as carcinogenic to humans. In recent years, a lot of work has gone how to precisely and accurately quantify the PAHs that are present in food. Biological monitoring is widely used to assess the possible health risk. The effects of short-term human exposure are as well not yet clear. There are studies proving that chronic exposure to PAHs have a mutagenic, carcinogenic and teratogenic effects on the human body.

Summary. PAHs are commonly found in food. Heat treatment affects the content of PAHs in food. PAHs negatively affect human health. Knowledge about biological activity of PAHs is important for a healthy society as well as the development of methods to assess exposure to PAHs.

Key words

carcinogenic compounds, dietary exposure, biomarkers, PAHs

Streszczenie

Wprowadzenie. Wielopierścieniowe węglowodory aromatyczne (WWA) powstają podczas niecałkowitego spalania materiałów organicznych. Są wszechobecne w środowisku, dlatego jesteśmy z nimi w stałym kontakcie.

Cel pracy. Celem artykułu jest porównanie różnych często spożywanych rodzajów żywności ze względu na zawartość WWA, a także omówienie wpływu tych związków na organizm człowieka, z uwzględnieniem metod oceny narażenia człowieka na WWA.

Stan wiedzy. Badania dowodzą, że głównymi czynnikami zanieczyszczenia żywności związkami z grupy WWA są procedury jej przetwarzania i metody obróbki termicznej, zwłaszcza procesy grillowania i smażenia. Międzynarodowa Agencja Badań nad Rakiem (IARC) sklasyfikowała wiele z tych związków jako prawdopodobnie rakotwórcze lub potencjalnie rakotwórcze, a jeden z nich, benzo[a]piren, jako rakotwórczy dla ludzi. Celem licznych prac opublikowanych w ostatnich latach było oznaczenie WWA w różnego rodzaju żywności. Monitoring biologiczny jest szeroko stosowany do oceny możliwego zagrożenia zdrowia człowieka po wpływem WWA. Skutki krótkotrwałego narażenia ludzi na te związki nie zostały dotychczas szczegółowo rozpoznane. Badania dowodzą jednak, że przewlekła ekspozycja na WWA ma działanie mutagenne, rakotwórcze i teratogenne na organizm człowieka.

Podsumowanie. WWA są powszechnie spotykane w żywności. Obróbka cieplna wpływa na ich zawartość w pożywieniu. Związki te negatywnie wpływają na zdrowie człowieka. Wiedza na temat ich aktywności biologicznej jest ważna dla zdrowia społeczeństwa, a także dla rozwoju metod oceny narażenia na WWA.

Słowa kluczowe

związki rakotwórcze, narażenie z dietą, biomarkery, WWA

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INTRODUCTION

One of the main causes of global pollution as a result of human activities is thought to be polycyclic aromatic hydrocarbons (PAHs). They are persistent environmental contaminants with a dangerous capacity for carcinogenesis and mutagenesis [1]. PAHs are organic substances with two or more condensed aromatic rings. Incomplete combustion of organic materials results in the production of PAHs, which are mostly released into the environment by various activities, such as transportation, industry, and home heating [2]. The process also occurs naturally (i.e., during a forest fire). The main anthropogenic sources of PAHs released into the environment are unquestionably automobile exhaust, petroleum refineries, power plant heating, waste combustion, sewage deposition, oil/gasoline spills, cigarette smoke, barbecue smoke, coke manufacture, and the burning of grass [3].

In addition to all environmental media (such as air, soil, and water), PAHs can also be found in a wide variety of foods consumed daily [4]. Increases in PAHs concentration levels have been noted in recent years in both industrialized and developing nations, which is likely due to the widespread intake of these chemicals in a variety of dietary products. There are several possible explanations for the presence of PAHs in food, including both natural and synthetic sources (i.e. cooking practices and industrial food processing) [5]. The environmental route, with regard to PAHs found in the soil and air, is one of their most frequent supply pathways for raw food (i.e. fruits and vegetables).

Because PAHs are both hydrophobic and lipophilic, they tend to accumulate in the food chain. After ingestion, PAHs can engage in metabolic activation in human mammalian cells, and can also be the result of DNA mutations [6]. Numerous studies have shown the negative effects of pollution on children's health, emphasizing their greater sensitivity than adults [7]. In particular, airborne pollution is linked to a number of health consequences in children, including asthma, neuro-development and allergy symptoms. This is of special concern in densely-populated urban regions [7].

Food is the main human exposure pathway for many people, especially non-smokers. One of the primary methods to determine exposure is biomonitoring, which involves analyzing biomarkers of exposure (often the pollutants themselves or their metabolites) in biological matrices. In addition, taking into account all sources of potential exposure, the concentration of biomarkers is thought to be a good indicator of the body's internal dose of pollutants [8–11].

The aim of the article is to compare the PAH content of different, often consumed types of food, and to discuss the effects of these compounds on the human body and identify methods for assessing human exposure to PAHs.

Types of PAHs in food. The following PAHs are commonly found in food products: pyrene (Pyr), fluorene (Flu), naphthalene (NA), phenanthrene (Phe), benzo[b] fluoranthene (BbF), benzo[k]fluoranthene (BkF), benzo[e] fluoranthene (BeF), anthracene (Ant), fluoranthene (Flt), benzo[a]anthracene (BaA), chrysene (Chry), dibenzo[a,h] anthracene (DbahA), benzo(ghi)perylene (BghiP), indeno[1,2,3-c,d]pyrene (IP) and benzo[a]pyrene (BaP) [12, 13, 14]. The International Agency for Research, on Cancer (IARC) has classified many of these compounds as probably carcinogenic (IARC group 2A) or possibly carcinogenic (group 2B) [15], and one of them, BaP, as carcinogenic to humans (group 1) [16].

European Commission Regulation on PAHs in Food. According to the Scientific Panel on Contaminants in the Food Chain of the European Food Safety Authority (EFSA), carcinogenic BaP is not an appropriate marker for the presence of polycyclic aromatic hydrocarbons in food, [17]. Instead, the panel recommended using a system of four compounds (PAH4), including BaP, BaA, BbF and Chry or eight compounds (PAH8): PAH4 + BkF, BghiP, DbahA and IP [17]. Oils and fats, cocoa beans and their derivatives, smoked meat and smoked meat products, muscle meat from smoked fish and smoked fishery products, smoked bivalve molluscs, processed cereal-based foods and baby foods for infants and young children, including infant milk and follow-on milk, and dietary foods for special medical purposes for infants, are all covered by the EU Regulation.

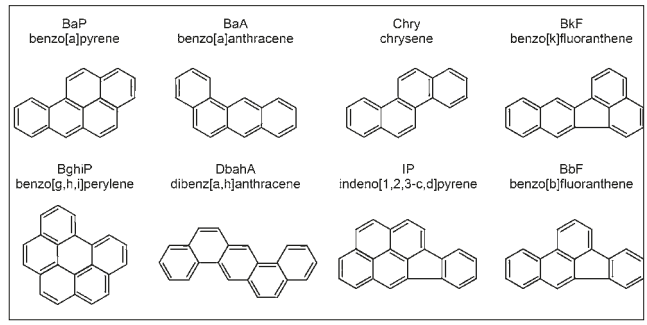

Figure 1. Chemical structures of compounds of the group PAH8

Fruits and vegetables. Plant-based food products have been found to contain a wide variety of PAHs. The ways in which they are contaminated are so varied that they can involve soil uptake, atmospheric exposure, and autogenous biosynthesis [4]. Soil contamination and water uptake from polluted sources are the three main ways that vegetables and fruits can absorb PAHs [18, 19]. Due to their increased surface area, which is susceptible to the deposition of PAHs, it has been discovered that leafy vegetables are typically more contaminated than stem vegetables [18]. PAHs concentrations in these products can range from a few to tens of μg/kg [20, 21]. However, the amount of pollution in leafy greens rises depending on the type of pollution source or site (such as next to industrial complexes and main roads) [19]. Similar to stem vegetables (cucumbers, eggplants, and tomatoes), root vegetables (potatoes, radishes, and carrots) are more likely to absorb PAHs from contaminated soil sites because they tend to grow deep into the ground. Research by Balbino et al [22] found that PAHs contamination in fried potatoes and similar products does not pose a direct threat to the health of consumers, the concentration of benzo(a)pyrene was up to 0.62 μg/kg and the sum of four PAHs (limitations by EU) was up to1.36 μg/kg. Fruits are less contaminated with PAHs than vegetables due to the reduced change in soil uptake [18].

Cereal grains. One of the main dietary ways by which people are exposed to PAHs is through cereal grains [21, 23]. The maximum level of PAHs in bread has not been defined, despite a gradual increase in the consumption rate of baked

and packaged bread. Due to the high temperature needed to bake bread, contamination cannot be avoided and can be dangerous. The effect of toasting bread has been studied with respect to the formation of PAHs, and the concentrations were between zero and several μg/kg [23]. Based only on bread consumption, the predicted daily intake of total PAHs varies from 0.1–10.6 ng/kg b.w./day [23].

Oil. Vegetable oils obtained naturally are free of PAHs. However, the way that they become contaminated is by air deposition on growing crops or during technological processing [24]. The presence of PAHs in vegetable oils is typically explained by the interactions of a variety of factors and processes. They also include the drying processes of the oil seeds (with the combustion of gases), contamination during solvent extraction, grinding the seeds, packaging material, and soil burn. Oils are polluted by heavier compounds with five or more condensed rings as a result of all these activities [13, 25]. Refined oils typically have lower levels of PAHs than crude oils [13, 25]. In samples of several commercially available oils (including olive oil, sunflower oil, canola oil and corn oil), the authors reported the presence of a total 15 PAHs at the level of some μg/kg [13, 25]. Most PAHs (about 90%) found in vegetable oils belong to the class of light PAHs; only rapeseed and sunflower oils contain an increased proportion (50–70%) of heavier PAHs [13]. According to EU Commission Regulation No. 835, the oils and fats intended for direct human consumption or use as an ingredient in food should contain no more than 2 μg of BaP and 10 μg of the sum of BaP, BaA, BbF and Chry per kg of product [17]. Heat treatment of oils can significantly increase PAH content [25].

Confectionary. Sweets such as biscuits, chocolates and candies are the favorite products consumed primarily by children and adolescents. For example, 16 PAHs were determined in 40 popular brands of biscuits from different countries and from those locally manufactured in the Nigerian market. The concentrations fluctuated in the range 18.4–880.3 μg/kg. They consist of wheat flour, vegetable oil, cocoa butter, lecithin, salt, gluten, raising agents, and antioxidants, but the difference in PAH content depended on the baking method, type of fuel and raw materials used, as well as the temperature of the oven. In the current study, PAHs concentrations were lower in locally manufactured biscuits than those imported from other countries, and 75% of the brands examined had BaP concentrations at levels below 1 μg/kg, while the rest were at the limit of acceptable concentration, or slightly above [26]. Confectionery products are often composed of chocolate and are discussed below.

Cocoa/chocolate. Due to the fact that sugar and cocoa butter are responsible for the presence of PAHs in sweets like chocolate, these items are an additional dietary source of PAHs. In chocolate candy samples, Kumari et al. [27] found that the total 15 PAHs concentration ranged from 2.7–235.0 μg/kg. The range for BaP was 0–12.8 μg/kg. According to EU Commission Regulation No. 835, tcocoa beans and derived products should contain no more BaP than 5 μg/kg fat, and the sum of 4 PAHs (BaP, BaA, BbF, Chry) should be below 35.0 μg/kg fat [17]. Due to the rigorous guidelines for the drying and smoking of cocoa, the content BaP in cocoa butter samples dropped from 7.8 μg/kg (fat) in 1999 to 3.8 μg/kg fat in 2012 [28, 29]. The sum of four PAHs determined in 2020 in raw and roasted cocoa beans of different origins was (below 0.45 μg/kg), i.e. much lower than 35.0 μg/kg fat [29].

Meat. The most common method by which people are exposed to PAHs is through the consumption of meat and meat products [5]. Thus, direct heating (at a high temperature) during the grilling process encourages the pyrolysis of food nutrients [30]. However, it was discovered that two pre-treatments (i.e. pre-heating and wrapping with aluminium and leaves) might lessen the influence of PAHs formation on the direct grilling of the meat products [31]. According to Onopiuk et al. [31], grilled meat samples that had been prepared with steam and a microwave did not produce any of the cancer-causing PAHs (BaP, BbF, and Fln). Onopiuk et al. [31] found that beef products had the highest level of BaP (12.5 μg/kg) of the harmful PAHs (Flt, BbF, and BaP) in grilled meats. Pork-based meats, such as smoked ham and belly pork ham, contained relatively large amounts of BaP in the concentration range of < 0.1–17.6 μg/kg [32, 33].

The formation of polycyclic aromatic hydrocarbons in charcoal-grilled meat can be significantly inhibited by using marinades prepared with wine vinegars, beer or tea, as well as different spices or vegetable, antioxidant-rich, additives [33, 34].

Coffee. One of the most popular drinks worldwide is coffee. PAHs in coffee samples were found to be of primary origin in green beans or were formed during the roasting process. The presence of PAHs in green coffee beans is mainly due to environmental pollutants found in the growing region [35, 36]. Since roasting is an essential procedure, this is the origin of PAHs contamination [36, 37]. Studies on the effect of mild coffee roasting on the level of PAHs contamination in beans show that the concentration levels of 19 PAHs ranged from 4.3–16.2 μg/kg in roasted coffee beans. The mild roasting parameters used did not lead to the formation of heavy PAHs. The carcinogenic BaP was not detected either in green or in roasted coffee beans [37].

Milk. Among the several beverages, milk is a crucial dietary component and a prime example of a dairy product. Depending on the type of milk product and the method of processing, milk passes through a number of distinct steps of heat treatment. In different types of milk samples (raw, pasteurized, ultra-high treated, semi-skimmed milk, and whole milk) the concentration of PAHs was measured [38]. BaP was found in all samples, albeit at low levels. Raw milk residues had a marginally smaller total of PAHs (5.4 μg/kg) than pasteurized milk residues (6.5 μg/kg). Sun et al. [39] determined 16 PAHs in milk from nine countries. The concentrations of total PAHs and BaP in samples from Oceania and Europe were in the range of 7.3–13.6 μg/kg and 0.46–0.83 μg/kg, respectively. The content of high molecular PAHs was lower in skimmed milks. Results suggest that drinking skimmed milk should only slightly increase the risk of being exposed to PAHs.

There was no discernible cancer risk in people, according to studies on the risk assessment of PAHs exposure from dairy products based on laboratory findings and dietary evaluations collected from questionnaires [40]. Children were at the highest risk because they consumed more dairy products than adults [41].

Other beverages. In general, in various alcoholic beverages, four PAHs concentrations did not exceed the permissible limit of 1 µg/kg or were not present [4]. Ciemniak and al. [42] determined the total content of 16 PAHs ranged from 41.5–2910.2 µg/kg in dried teas and 52.9–2226.0 ng/L in infusions, but the concentration of BaP was below quantification limit. The total toxicity of tested teas largely corresponded to the sum of 4 PAHs chosen by the European Food Safety Authority as an indicator of PAHs in food. Estimated PAHs uptake and margin of exposure indicated a low health risk associated with drinking tea infusions [42].

Exposure assessment methods. Biological monitoring is widely used to assess the possible health risk by the measurement of the individual internal dose to observe the hazard the specific substance may induce. Biological monitoring is the determination of a parent chemical or its metabolites in human biological material: urine, hair, nails, blood, body fluids and/or expired air [40]. The biomarkers used in this method are any molecular, cellular or physiological indicators, objectively measured, assessed and analyzed, which are used to assess exposure to xenobiotics and their potential impact on the population. Biomarkers can be classified into three major kinds: exposure, effect, and susceptibility. They are measured through pathogenic processes or pharmacologic responses to a therapeutic intervention. On analysis, there are significant differences between those classifications [41, 52].

Biomarkers of exposure. The biomarkers of exposure cover chemicals or their metabolites, as well as all the products of interactions between specified target cells or molecules measured in the human body and the aforementioned chemicals. The biomarkers of internal, effective dose exposure to PAHs are distinctive as they consist of the parent chemical, which is determined in circulating anti-DNA adduct antibodies, protein (haemoglobin and albumin), PAHs adducts or buccal cell PAH-DNA adducts, leukocytes, tissues, and urinary metabolites [53, 54].

Biomarkers of effect. Biomarkers of effect are used to define and outline the impact of exposure to chemicals, including contaminants, on an intended biological system, for instance, blood. Consequently, there are cellular, molecular, and even systematic results observed before any clinical symptoms are revealed. Several studies show that DNA damage is the fatal result of air pollution. The 'bulky' DNA adducts are considered to be primarily noxious as they are related to aromatic compound exposure, for instance, PAHs [55]. The groups tested are most often exposed workers. Biomarkers are used to calculate the carcinogenic and genotoxic risk of PAHs, for example, in the case of DNA adducts recovered from urine or blood which may reveal the risk of genotoxicity. A part of these biomarkers of effect contains standard cytogenetic assays, a good example of which are sister chromatid changes, micronuclei, chromosomal aberrations, or the high frequency of RAS oncogene (one of the cancer genes) mutations [56].

Table 1. Content, limit values and main sources of PAHs contamination depending on type of foodstuff

Type of foodstuff	Content of PAHs [µg/kg]	Main source of contamination with PAHs	Limit values according to The European Commission Regulation on PAHs in Food [17]	References
Fresh fruits and vegetables	0.01–0.5 (individual PAHs) 10.0–458.0 (total of 16 PAHs)	– soil – water uptake from polluted sources – air contaminants	not estabilished	[18, 19, 20, 21, 22, 43]
Processed cereal-based foods	Bread: 0–279.0, mostly 0–3.0 Biscuits: 0–880	– contamination of ceral grain – thermal treatment (baking, toasting)	1 µg/kg BaP 1 µ/kg PAH4	[13, 21,23] [26]
Oil (plant base)	0.5–234.3 (3751.0–7586.0; edible oil, China)	– environmental polluting of raw vegetables and plants – manufacturing processes (drying gases, organic solvent extraction, grinding the seeds, packaging material)	2 µg/kg BaP 10 µg/kg PAH4	[13, 24, 44, 45] [25]
Cocoa/chocolate	15PAHs: 0.2–235.9 BaP: 0–12.8	– smoke contamination during cocoa beans drying – cocoa shell	5 µg/kg fat BaP 30 µg/kg PAH4	[27, 28, 29]
Meat products	Smoked meat products: 10–100.0 Grilled meat: 0.1–18.0	– smoking and charcoal-grilling processes	Smoked meat and smoked meat products: 2–5 µg/kg BaP 12–30 µg/kg PAH4 Heat treated meat products sold to the final consumer: 5 µg/kg BaP 30 µg/kg PAH4	[5, 13, 30, 31, 32, 34, 46, 47]
Coffee and tea	Roasted coffee beans: 3 to 50 Dryied tea leaves: 2.8–2910.2	– environmental deposits – heating/roasting cofee and smoking tea leaves processes	not estabilished	[13, 35, 36, 37, 42, 48]
Milk	5.4–13.6	– rearing system (fodder and potential contaminated soil) – ruminant's source of exposure (ingestion during grazing, contaminated water and air)	not estabilished	[38, 39, 40, 49
Infant based formulation	0.1–2.5	– milk and other food components (vegetables, meat) contamination – drying processes of milk,	1 µg/kg BaP 1 µg/kg PAH4	[50, 51]

Biomarkers of susceptibility. The biomarkers of susceptibility usually characterize the response of the population to exposures. They can also be used to determine and label potentially sensitive population subgroups. Importantly, all the separate individuals with biomarkers of effect will not develop the disease, as proved by studies of genetic polymorphism. Those studies recognize individuals with enzyme types that are more likely to be affected by a chemical, which discloses the relation between genetic predisposition and an individual being affected by carcinogen-induced cancer. Genetic susceptibility is mainly the effect of variation in genes for carcinogens which metabolize enzymes, such as isoenzymes of cytochrome P-450 and glutathione-S-transferases (GSTs), variations in genes for the repair of DNA adduct, polymorphism in enzymes involved in the activation of PAHs to mutagens and subsequent detoxification (CYT 1A1, GSTS 1, GSTP 1, and NAT 2). Susceptibility biomarkers play a crucial role in assessing the mechanism of toxicity [41, 57, 58].

Impact of PAH on the human body. The main factors influencing exposure to human health are the concentration of PAHs, as well as the time, route of exposure, and naturally the innate toxicity of the PAHs [58, 59]. There are also various determinants, such as subjective which include age and general health condition of the exposed individual [60]. Metabolism of PAHs in the body takes place with the involvement of various liver enzymes. The main metabolic activation pathways of PAHs, exemplified by the carcinogen BaP, are shown in Figure 2 [61, 62].

Carcinogenicity. Discussing carcinogenicity, PAHs employ their activity both directly and indirectly, with their oxygen derivatives of PAHs (OPAHs) and nitrogen derivatives (NPAHs), such as 1-nitropyrene, 1,8-dinitropyrene, and 3-nitrofluoranthene, being active by the direct route and do not require metabolic activation [63]. Epidemiological studies have shown that there is a correlation between PAH-DNA adducts and exposure to PAHs, also taking into account the correlation between the source of exposure, which can be a coking plant or smoking a cigarette, and PAH-DNA adducts in blood cells [64, 65]. The studies also show the evolution of a refined repair system, which eliminates DNA adducts from the genome via nucleotide excision repair [66]. There are two significant condition that have to be taken into consideration. First of all, the adducts may be left unrepaired, which results in permanent mutation; secondly, the mutations may be situated at critical sites, such as tumour suppressor genes or oncogenes, which may result in cellular transformation leading to the development of tumours. There are cases of specific mutations in the Tp53 gene, which is the most common one to be mutated in humans, and are associated with exposure to very particular carcinogens [66, 67]. Laboratory studies have proven that animals can develop lung cancer, stomach cancer, and skin cancer from inhalation, ingestion, and skin contact, respectively, after long periods of PAHs exposure. Respectively, human studies prove that long-term occupational exposure to substances containing PAHs raises the likelihood of lung, bladder, gastrointestinal, and skin cancer development [68]. The eight PAHs compounds: BbA, BaP, BbF, BkF, Chry, DbahA, IP and BghiP, have been classified by both the EPA and IARC as carcinogens or probable human carcinogens [69].

Genotoxicity and immunotoxicity. Another critical point in this discourse is the genotoxicity and immunotoxicity of PAHs. Most PAHs are not actually toxic themselves and need to be metabolized to their diol epoxides, which at that point react with DNA to induce genotoxic damage. The effects have been shown in studies focusing on rodents and *in vitro* tests using mammalian cell lines, including human ones [70]. Duca et al. evaluated the impact of exposure to PAHs on non-monotonic modulation of DNA and RNA (hydroxy)methylation in a rat mode which included 64 rats. The mix of PAHs consisted of 16 compounds. Eight rats

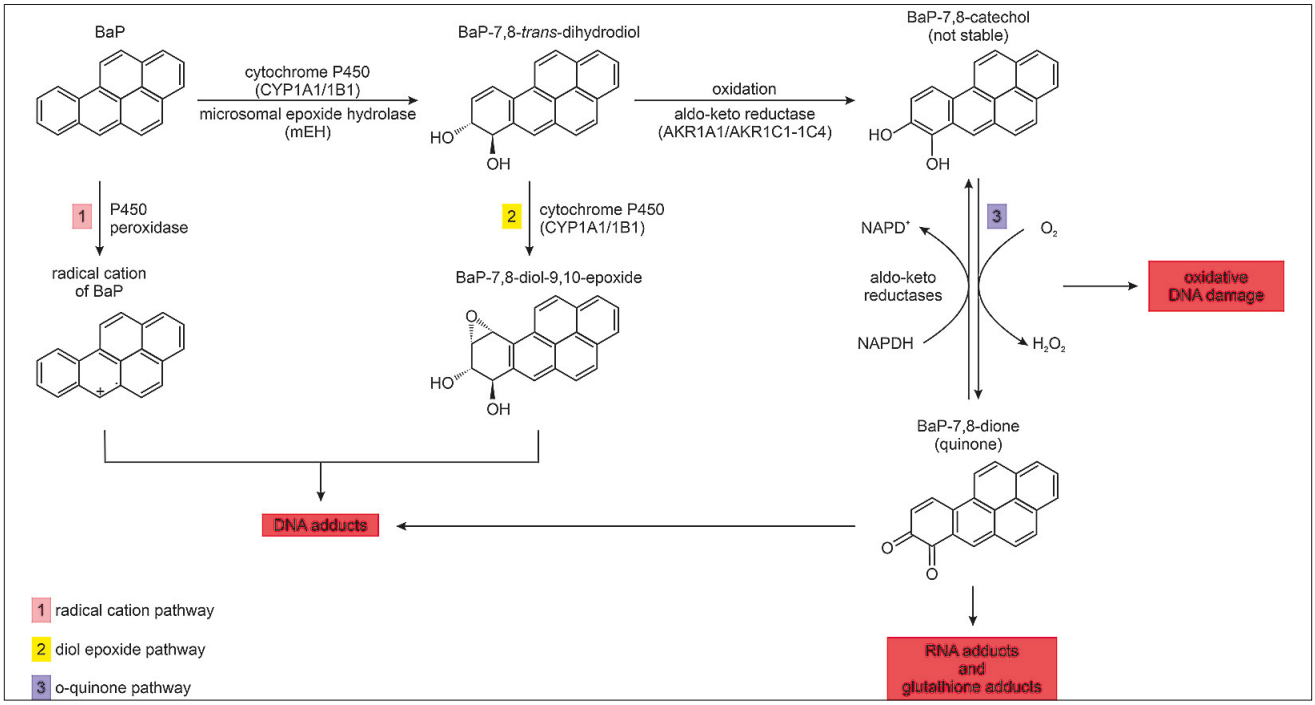

Figure 2. Major metabolic activation pathways of PAHs on the example of BaP [61, 62]

were randomly allocated to each of the experimental groups receiving 10–800 μg/kg body weight of each compound included in the mix, by gavage, three times per week over a 90-day period. The control group received only vegetable oil.. Urine samples were collected for 24 h prior to day 90. Livers were dissected immediately after euthanization. Fifty metabolites of PAHs (OH-PAHs) were assessed. Glutathione (GSH) and glutathione disulfide (GSSG) concentrations, DNA and RNA (hydroxy)methylation at the C5 position of cytosine (m5C and hm5C) and tetrahydroxylated polycyclic aromatic hydrocarbons (tetra-OH-PAHs), which are involved in DNA-adduct formation in liver tissue, were also analyzed. 41 OH-PAHs were detected in urine. GSH/GSSG ratio increased in the rats treated with lower treatment levels. Increased levels of m5C-DNA and hm5C-DNA were observed at the highest PAHs concentration. Several tetra-OH-PAHs have been identified and quantified in liver DNA samples. Tetra-OH-PAHs in DNA from higher treatment levels were about 3–4 times higher than in the control group [71].

It has been proved that PAHs exposure causes two types of health damage, oxidative damage and bulky adducts, but it may also result in the formation of apurinic sites. The oxidative damage effect is the formation of 8-oxo-dG, which is by far the most mutagenic lesion. The damage is induced by the generation of reactive oxygen species (ROS) from the futile redox cycling of PAHs metabolites, while the bulky adducts proceed from the covalent attachment of PAHs to DNA bases. The third type consists of apurinic sites (AP sites), that emerge when unstable bulky adducts are lost from DNA. On the other hand, with large damage caused by bulky adducts and oxidative damage, the AP sites occur with a lower frequency. The significance of PAHs genotoxicity is mostly observed in carcinogenicity processes, as well as certain forms of developmental toxicity; they were also proven to suppress immune reactions in tests on rodents. Despite numerous studies, the mechanisms of PAHs-induced immunotoxicity have so far not been clearly explained. Nevertheless, it is believed that immuno-suppression may impact the mechanisms by which PAHs induces cancer [72].

Teratogenicity. Another matter to be discussed on this topic is teratogenicity. Tests conducted on animals have shown that individuals exposed to PAHs, e.g. BaA, BaP, and NA, suffer embryotoxic effects. Studies at the Centre for Children's Environmental Health reveal that transplacental exposure to PAHs pollution is connected with such negative outcomes as heart malformation, low birth weight, and premature delivery. In the case of prenatal high exposure to PAHs, there is a risk of a decrease in white matter volume in the left hemisphere of the brain, causing lower cognitive skills and functions, behavioural issues, and even childhood asthma [73].

Acute health effects. The effects of short-term human exposure are also not clear. There are studies proving that occupational exposure to high levels of pollutant mixtures containing PAHs is most likely to cause a variety of symptoms, such as nausea, vomiting, diarrhoea, eye irritation, and even confusion [74]. However, it has not been explained which components were the factors for these effects. It has also been reported that mixtures of PAHs resulted in skin irritation and inflammation. Skin irritants, such as BaP, and naphthalene (although anthracene is also known to cause the irritation), are widely found in skin sanitizers, all of which may cause allergic reactions for both humans and animals [74, 75].

Chronic health effects. Numerous studies have been conducted on the chronic health effects of PAHs which have been established that long-term exposure results in various symptoms, such as: skin redness and skin inflammation (when chronic exposure is possible), decreased immune functions, kidney and liver damage, breathing issues, asthma-like symptoms, and cataracts. One of the PAHs, NA, may cause damage as large as red blood cell breakdown if ingested or inhaled in big amounts [76]. Furthermore, studies of the bioassays have reported PAHs to have the ability to impact human and animal endocrine systems [75]. The significant studied pathway which is connected with the endocrine-disrupting activities of PAHs is estrogen. The studies concern mostly estrogen receptors and aryl hydrocarbon receptors, and report several possibilities, including suppression of the PAHs activities through their pathways or direct interaction between PAHs and receptors. However, the mechanisms responsible for PAHs activation remain unclear [76].

Schraplau et al. conducted studies on rat hepatocytes to investigate the effect of benzo(a)pyrene on the degradation of thyroid hormones and the formation of glucuronoids. Hepatocytes were treated with different concentrations of benzo(a)pyrene (1–60 μM) dissolved in DMSO. The cell culture was carried out for 72 h. The LC-MS/MS method was used to clarify the physiological role of the degradation of thyroid hormones and the formation of thyroid hormone glucuronides by benzo(a)pyrene in control cultures and induced hepatocytes. Induction with benzo[a]pyrene increased the velocity of T3 (triiodothyronine) degradation in hepatocyte cultures. Induction with benzo[a]pyrene shortened the mean of the T3 half-life by 28%. Similarly, the mean of the rate of T4 (tetraiodothyronine) degradation increased. Glucuronidation was enhanced in hepatocytes induced with benzo(a)pyrene. T3 and T4 glucuronidation was increased 1.7-fold and 6-fold by benzo[a]pyrene, respectively [77].

CONCLUSIONS

After the revision of the concentrations and fate of PAHs in the environment and evaluation of these compounds in food, the main risk factor for public health (for non-smokers) are PAHs ubiquitous in thermally-processed foods. Processing procedures and cooking methods strongly impacted on the level of PAHs contamination in food. After PAHs are ingested, they can undergo metabolic pathways. The final reaction products can bind to DNA, thus exerting toxic, mutagenic, and/or carcinogenic effects. Consequently, the development of accurate, sensitive, and efficient analytical methods and techniques to provide a comprehensive PAHs assessment, practical health guidelines for internal and external PAHs exposure, as well as their further implementation, are crucial. Future studies should focus on an effective methods for monitoring PAHs exposure, with the aim of minimising their risk to health. Although concentrations of PAHs do not always exceed the limit values, more attention should be paid to the conditions of food preparation. Moreover, the dissemination of knowledge about the sources and biological activity of PAHs is important for the sake of a healthy society.

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