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RESEARCH ARTICLE

Risk assessment of four polycyclic aromatic hydrocarbons in South Korean sesame oil products

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Abstract

In this study, the PAH content of sesame oil was analyzed, with particular emphasis on four representative compounds (PAH4): benzo[a]anthracene (BaA), benzo[a]pyrene (BaP), benzo[b]fluoranthene (BbF), and chrysene (CHR). Thirty commercially available sesame oil products were randomly selected and analyzed using high-performance liquid chromatography coupled with fluorescence detection (HPLC-FLD). The detection rates for each PAH were as follows: BaA (93.33%), BaP (66.67%), BbF (60.00%), and CHR (80.00%). The mean concentrations observed were 2.21 µg/kg for BaA, 1.28 µg/kg for BaP, 2.05 µg/kg for BbF, and 3.34 µg/kg for CHR. To evaluate the margin of exposure (MOE), the estimated daily dietary exposure was calculated based on the detected PAH4 compound content and daily consumption. Consequently, all MOE values exceeded the threshold of 10,000, thereby confirming a low health risk. As a result, the representative PAH4 compounds should be considered when managing overall PAH exposure.

Keywords PAH4 · Sesame oil · HPLC-FLD · Exposure assessment · Margin of exposure

Introduction

Polycyclic aromatic hydrocarbons (PAH) are organic compounds that consist of two or more benzene rings arranged linearly or in condensed clusters. Benzo[a]anthracene (BaA) and chrysene (CHR), which contain four benzene rings, are classified as light PAHs, whereas benzo[a]pyrene (BaP) and benzo[b]fluoranthene (BbF), which has five benzene rings, are classified as a heavy PAHs (Sahoo et al., 2020). In terms of their critical effects on wildlife and humans, PAHs induce estrogenic effects, which may affect their toxicity and carcinogenicity (Kummer et al., 2008). Endocrine-disrupting chemicals affecting the estrogen pathway pose critical risks to hormonal function, embryonic development, and reproductive health (de Souza et al., 2024; Fang et al., 2023). The International Agency for Research on Cancer has included BaP in Group 1, categorizing it as a substance that causes human cancer (IARC, 2010). Consequently, various countries have regulated PAH concentrations in processed foods by establishing maximum detection limits (ML) based on human health-based guidance values. The European Food Safety Authority (EFSA) determined the MDLs of PAH4 compounds (BaP, BaA, BbF, and CHR) based on the recommendation that regulating BaP content only is insufficient for PAH safety management (EC, 2011).

PAHs have been detected in environmental samples containing in/out-door air (Batbaatar et al., 2025). Moreover, PAHs are generated in food due to incomplete combustion and thermal degradation of organic substances during cooking and processing (Xu et al., 2024). In Sweden, PAH contamination levels in smoked meat and fish exceed the maximum PAH levels set by the European Commission (Wretling

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et al., 2010). Additionally, BaP was detected in 129 tea samples distributed in Europe at levels similar to the European Union's (EU) permissible limits (Speer et al., 1990).

In particular, PAH contamination levels are higher in edible oils than in other foods because oils require heating and drying processes. Camargo et al. (2011) revealed that commercial soybean oils in Brazil were contaminated with PAHs at varying levels. BaP has also been detected in safflower, evening primrose, and flaxseed oils (Silva et al., 2018). In India, 88.5% of 296 edible oil samples were contaminated with PAHs, with virgin olive oil exhibiting the highest levels (Pandey et al., 2004). Similarly, 32.4% of 139 Chinese vegetable oil products exceeded the EU permissible limits (Liu et al., 2023).

Sesame oil is one of the most widely consumed edible oils in Northeast Asia. According to Kim et al. (2020), about 65% of the global annual sesame production is used for edible oil in food preparation. The distinctive nutty aroma of sesame oil is the primary reason for its extensive use as seasoning and a food source. In addition, the oil serves as a source of various nutrients, including unsaturated fatty acids (oleic acid and linoleic acid), tocopherols, plant sterols, and lignans (Hoyos et al., 2024).

However, roasting sesame seeds during oil production can lead to the formation of polycyclic aromatic hydrocarbons (PAHs), as noted by Ji et al. (2019). Consequently, sesame oil has been identified as a significant source of PAH contamination (Shi et al., 2016). In light of this, the present study aimed to determine the quantitative contamination levels of PAH4 compounds in sesame oil products available in the South Korean market between 2022 and 2023. Moreover, margin of exposure (MOE) was determined to assess the risk of PAH exposure to the public via sesame oil consumption. Thus, the study findings will aid in confirming the hazardous levels of PAH4 compounds in sesame oils produced via various processing methods.

Materials and methods

Chemicals and reagents

BaA (CAS No. 56-55-3), CHR (CAS No. 218-01-9), BbF (CAS No. 205-99-2), BaP (CAS No. 50-32-8), and *N,N*-dimethylformamide were purchased from Sigma-Aldrich (St. Louis, MO, USA). The PAH4 standard and the internal standard 3-methylcholanthrene (CAS No. 56-49-5) were obtained from Toronto Research Chemicals (Toronto, Canada). Acetonitrile (CAS No. 75-05-8), hexane (CAS No. 110-54-3), and dichloromethane (DCM; CAS No. 75-09-2) were purchased from Burdick & Jackson (Ulsan, Korea). Sodium sulfate (Na_2SO_4, CAS No. 7757-82-6) was used for dehydration and obtained from WAKO (Osaka, Japan). Silica cartridges (Certified Sep-Pak Silica 6 cc Vac Cartridge, 1 g Sorbent per Cartridge, 55–105 µm, Waters, Milfors, MA, USA) were utilized for solid-phase extraction and purification. Polytetrafluoroethylene syringe filters with a pore size of 0.45 µm were acquired from Teknokroma (Barcelona, Spain). All other chemicals and reagents were obtained from commercial sources.

Sample collection and pre-treatment for PAH4 analysis

Sample collection

To assess exposure, a comprehensive collection of sesame oil samples was conducted nationwide in South Korea. Thirty distinct products were sourced from various manufacturing regions for analysis. A total of 30 sesame oil samples were analyzed, consisting of 23 samples produced in factories and 7 samples produced in local mills. The factory-produced samples were purchased online, while the mill-produced samples were obtained directly from local mills. All samples were produced in South Korea in 2022.

Extraction procedure

For extraction, 10 g of each sample was weighed, dissolved in 100 mL of hexane, and spiked with 1 mL of internal standard solution. The mixture was transferred to separatory funnel I, followed by addition of 50 mL of *N,N*-dimethylformamide–water (9:1). After shaking and phase separation, the aqueous layer was transferred to separatory funnel II. Extraction was repeated twice by adding 25 mL of *N,N*-DMF–water to the hexane layer, and all aqueous layers were combined in funnel II. Then, 100 mL of 1% sodium sulfate solution was added, mixed, and followed by 50 mL of hexane. After separation, the hexane layer was moved to funnel III, where 35 mL of *N,N*-DMF–water was added. This step was repeated twice, and the aqueous layers were combined. Next, 40 mL of water was added to the funnel and shaken thoroughly; the aqueous phase was discarded twice. The remaining hexane layer was dehydrated using filter paper containing approximately 15 g of anhydrous sodium sulfate, filtered, and concentrated under reduced pressure at temperatures below 40°C to approximately 2 mL.

Sample purification and HPLC-FLD analysis

For purification, a solid-phase extraction (SPE) cartridge was pre-activated with 10 mL of dichloromethane (DCM) and 20 mL of hexane at a flow rate of 2–3 drops per second. The concentrated sample was loaded onto the cartridge at 1 mL/min and eluted with 5 mL portions of hexane/DCM (3:1). The eluate was collected and kept in a

water bath maintained below 40°C, then evaporated under nitrogen gas. The residue was dissolved in acetonitrile to a final volume of 1 mL, filtered through a 0.45-µm membrane filter, and subjected to HPLC-FLD analysis. The analytical conditions, including column specifications and detection wavelengths, are provided in Supplementary Table S1.

Verification of quantitative analysis of PAH4 compounds using HPLC-FLD system

The analytical method for determining PAH4 compounds in sesame oil was validated in accordance with the guidelines established by the Korean Ministry of Food and Drug Safety (MFDS, 2021), with minor modifications.

Linearity was evaluated using standard solutions of PAH4 compounds at six concentrations (2–100 µg/kg) with 3-methylcholanthrene (20 µg/kg in acetonitrile) as the internal standard, and calibration curves constructed from peak areas showed good linearity within the tested ranges. The limits of detection (LOD) and limits of detection quantification (LOQ) were determined from three replicate calibration curves using the formula:

$$\mathrm{LOD} = \frac{3.3\sigma}{\mathrm{s}}$$

$$\mathrm{LOQ} = \frac{10\sigma}{\mathrm{s}}$$

σ = Mean of standard deviation of the y-intercept; s = Slope mean of calibration curve.

BaA and BaP were tested in the range of 0.2–10 µg/kg and CHR and BbF in the range of 2–30 µg/kg, and the calculated values were expressed in µg/kg. Precision was assessed as the relative standard deviation (%RSD) from intra-day tests (three replicate analyses at 2, 10, and 50 µg/kg within a single day) and inter-day tests (once daily for three consecutive days), while accuracy was calculated as the ratio of the measured mean value to the theoretical value.

$$\text{Precision (\% RSD)} = \frac{\text{standard deviation of the results}}{\text{Mean}}$$

$$\text{Accuracy (\%)} = \frac{\text{Mean of the determined value}}{\text{Theoretical value}} \times 100$$

Recovery was determined using unroasted sesame oil, which was confirmed to be free of PAH4 contamination, as a blank matrix. Recovery was measured at two spiking levels (2 and 50 µg/kg), reflecting the hydrophobic interaction of PAHs with the lipid fraction of sesame oil.

Exposure assessment

An exposure assessment was conducted based on the PAH4 compound concentrations in sesame oil and intake data from the 2022 Korea Health Industry Development Institute (KHIDI). The data used for this assessment are presented in Supplementary Table S2. According to the GEMS/Food-EURO guideline (1995), non-detected values should be handled based on their non-detection rates. For the risk characterization of PAH4, which are considered genotoxic carcinogens, the Margin of Exposure (MOE) approach was employed. This methodology is recommended by the European Food Safety Authority (EFSA) as it is scientifically appropriate for assessing health risks from substances that are both genotoxic and carcinogenic, for which a safe threshold cannot be determined. To calculate the MOEs, benchmark dose lower-bound confidence limit 10% ($BMDL_{10}$) values of 70,000 ng/kg·b.w./day for BaP and 340,000 ng/kg·b.w./day for PAH4 compounds, recommended by the EFSA (EFSA, 2008), were applied. Daily dietary exposure to the PAH4 compounds and MOE values were calculated using the equations provided below. A higher MOE value indicated greater safety.

Specifically, an MOE ≥ 10,000 indicated a low risk level (EFSA, 2008). Heatmaps were constructed using Prism 8.0.2 to visualize and compare the relative levels of daily dietary exposure and MOE across age and sex groups.

$$\text{Daily dietary exposure}\left(\frac{\text{ng}}{\text{kg}}\cdot\frac{\text{bw}}{\text{day}}\right) = \frac{\text{Total PAH4 compound concentration (ng/g)} \times \text{daily consumption (g/day)}}{\text{Average body weight (kg)}}$$

$$\mathrm{MOE} = \frac{BMDL_{10}}{\text{Estimated daily dietary esposure (ng/kg} \cdot \text{bw/day)}}$$

Results and discussion

Validation of quantitative analysis method of PAH4 compounds using HPLC-FLD system

The method for detecting PAH4 compounds in sesame oil was validated according to the guidelines of the Korean Ministry of Food and Drug Safety (MFDS, 2021). After confirming that no significant differences in fatty acid composition were observed between roasted and unroasted sesame oils (Supplementary Table S3). Key parameters, such as selectivity, linearity, LOD, LOQ, precision, and accuracy, were evaluated during the validation process.

The peaks were well separated without overlapping, and the baseline remained consistently stable, thus demonstrating good selectivity. The calibration curves for each standard substance were linear with correlation coefficients of 0.997 or higher. PAH4 standard solutions were prepared at five concentrations: 2, 5, 10, 20, and 50 µg/kg. Each concentration was measured thrice to establish calibration curves and assess linearity (Table 1). The LOD and LOQ values complied with the specified standards (Table 1). The precision (%) values for BaA, BaP, BbF, and CHR ranged between 0.35–6.83%, 0.42–3.40%, 0.56–3.38%, and 0.95–11.55%, respectively. The accuracy (%) values for BaA, CHR, BbF, and BaP based on the daily and intraday experiments ranged between 105.78–115.28%, 109.42–117.87%, 110.94–117.26%, and 97.58–115.55%, respectively (Table 1).

Unroasted sesame oil was considered a matrix free of PAH4 compound contamination, confirming that roasting is the primary contributor to PAH formation in sesame oil (Ji et al., 2019; Shi et al., 2016), and was used as the matrix to determine recovery rates. As a result, the recovery rates for BaA, BaP, BbF, and CHR were 107.11–113.72%, 98.77–117.81%, 92.40–118.39%, and 101.13–118.20%, respectively (Table 1). These results are consistent with the recovery rate guidelines.

PAH4 compound content in South Korean sesame oil

In this study, PAH4 compounds, which are endocrine-disrupting substances (Hong et al., 2017), were detected in

Table 1 PAH4 compound content in 30 type of sesame oils including individual and total PAH4 compound levels

PAH4	R^2	LOD (µg/kg)	LOQ (µg/kg)	Accuracy (%)	Precision (RSD%)	Average recovery	
						Accuracy (%)	Precision (RSD%)
BaA	0.9987	0.33	0.99	105.78–115.28	0.35–6.83	107.11–113.72	4.42–6.42
BaP	0.9985	0.49	1.49	109.42–117.87	0.42–3.40	98.77–117.81	7.63–10.96
BbF	0.9990	1.03	3.01	110.94–117.26	0.56–3.38	92.40–118.39	5.82–9.43
CHR	0.9995	0.34	1.02	97.58–115.55	0.95–11.55	101.13–118.20	7.51–18.57

LOD limit of detection, *LOQ* limit of quantification, *RSD* relative standard deviation, *PAH* polycyclic aromatic hydrocarbon, *BaA* benzo[a]anthracene, *BaP* benzo[a]pyrene, *BbF* benzo[b]fluoranthene, *CHR* chrysene

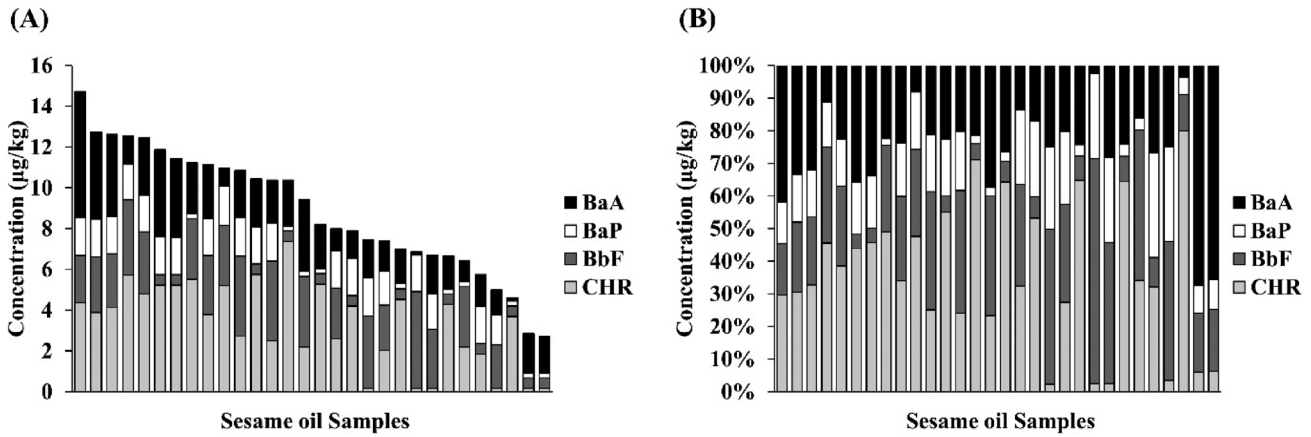


Fig. 1 PAH4 compound concentrations in 30 sesame oil samples. (**A**) Stacked bar chart showing the concentrations of the PAH4 compounds: BaA, BaP, BbF, and CHR. (**B**) 100% stacked bar chart presenting the relative contribution of each compound to the total PAH4 compound concentration in each sample. *PAH* polycyclic aromatic hydrocarbon, *BaA* benzo[a]anthracene, *BaP* benzo[a]pyrene, *BbF* benzo[b]fluoranthene, *CHR* chrysene

South Korean sesame oil products, and the daily exposure risk through sesame oil intake was assessed. The mean concentrations of BaA, BaP, BbF, and CHR in the 30 sesame oil samples were 2.21 ± 1.29, 1.28 ± 0.74, 2.05 ± 1.36, and 3.34 ± 2.02 μg/kg, respectively. A key finding of this study is that PAH4 compounds were non-detectable in the unroasted sesame oil. This result strongly indicates that the roasting process is the primary source of PAH formation in sesame oil. This interpretation is consistent with previous studies, which also identified thermal processing as the main contributor to PAH generation in vegetable oils (Ji et al., 2019; Shi et al., 2016). The overall mean concentration of PAH4 was 8.89 ± 3.05 μg/kg, with a range of 2.72–14.73 μg/kg (Fig. 1A). Regarding the contribution of each compound to total contamination, BaP exhibited the lowest mean concentration, whereas CHR was the highest, followed by BaA and BbF (Fig. 1B). The detection rates among the 30 sesame oil samples were 93% for BaA, 80% for CHR, 67% for BaP, and 60% for BbF (Fig. 1B). The concentrations of each PAH are listed in Supplementary Table S4. Non-detected compounds were recorded as "< LOD," indicating concentrations below the threshold. The non-detection rates were 7%, 33%, 40%, and 20% for BaA, BaP, BbF, and CHR, respectively. As discussed in the Introduction, PAH4 compounds can form during the thermal processing of vegetable oils, with high-temperature roasting significantly promoting their generation (Shi et al., 2016; Xu et al., 2024). Oils such as sesame and peanut oil, which are typically extracted from roasted seeds to enhance flavor and aroma, have been shown to contain higher levels of PAH16 compared to other vegetable oils (Ji et al., 2021). Supporting this, Kang et al. (2019) reported that replacing sesame oil with a higher proportion of brown rice oil in seasoned-roasted laver significantly reduced PAH content.

In the context of PAH4 monitoring in edible oils, a study by Shi et al. (2016) reported that one sesame oil sample collected in China exceeded both the PAH4 regulatory limit of 10 μg/kg and the BaP limit of 2 μg/kg. Notably, their analysis across 85 edible oil samples identified sesame oil as having the highest levels of PAH4 contamination, with concentrations ranging from 1.52 to 14.68 μg/kg. Supporting this pattern, Chung and Lau (2015) found that, among 88 edible oil samples, one sesame oil product exceeded the BaP threshold, and two exceeded the PAH4 limit.

Reflecting similar trends, the present study also observed that although BaP concentrations in all sesame oil samples remained below the regulatory limit, the combined concentration of the four PAH4 compounds surpassed the EFSA safety threshold (10 μg/kg) in multiple samples. These results point to the importance of shifting regulatory focus from BaP alone to the broader group of PAH4 compounds, as emphasized in recent assessments (Lee et al., 2019; Li et al., 2023).

To further contextualize these findings, previous research has examined the detection patterns of individual PAH4 compounds in sesame oil. For example, Lee et al. (2019) analyzed 129 sesame oil samples and found that the mean concentrations followed the order of CHR (0.41 ng/g) and BaA (0.41 ng/g) > BbF (0.35 ng/g) > BaP (0.18 ng/g). Similarly, Speer et al. (1990) reported CHR, BbF, and BaA in sesame oil at detection levels of 0.6 ng/g, 0.1 ng/g, and less than 0.1 ng/g, respectively, while BaP was not detected. In a broader screening of PAH16 compounds, He et al. (2025) noted that CHR showed the highest detection frequency. Likewise, Rascón et al. (2018) identified acenaphthylene, anthracene, fluoranthene, and CHR in sesame oil, with CHR being the only representative compound from the PAH4 group detected.

Taken together, these studies consistently highlight CHR as the major contributor to PAH4 contamination in sesame oil—a finding that aligns well with the present study's results (He et al., 2025; Lee et al., 2019; Rascón et al., 2018; Speer et al., 1990).

Daily PAH4 compound exposure via sesame oil intake in South Korea

To determine the daily dietary exposure to PAH4 compounds, intake levels were estimated based on KHIDI (2022) data, using one-half of the LOD for non-detected values in accordance with the GEMS/Food-EURO guidelines (1995). The calculated exposure levels (ng/kg·bw/day) are provided in Supplementary Table S5. As shown in Fig. 2, exposure values across age and sex groups were visualized as a heatmap, where darker shades reflect higher exposure. CHR contributed most prominently to total exposure, particularly in the 1–2 years age group, where the intake population had the highest CHR exposure (0.224 ng/kg·bw/day). In contrast, BaP exhibited the lowest exposure (0.086 ng/kg·bw/day) in the same age group (Fig. 2A).

Exposure estimates according to age and sex indicated that children in the 1–2 years and 3–5 years age groups age groups exhibited relatively higher exposure levels (Fig. 2). In these age groups, females had a higher exposure than that experienced by males. In the total (sex-combined) group, the daily dietary exposure to PAH4 compounds ranged between 0.150–0.469 ng/kg·bw/day (whole population) and 0.213–0.597 ng/kg·bw/day (intake population) (Fig. 2B). The highest exposure was observed in the 1–2 years age group, with the intake population showing a daily dietary exposure of 0.597 ng/kg·bw/day (Fig. 2B). Conversely, the 12–18 years and 19–29 years age groups had the lowest intake-population exposures, both at 0.213 ng/kg·bw/day (Fig. 2B). Among the intake population in the 1–2 years age group, the daily dietary exposure was 0.479 ng/kg·bw/day for males and 0.746 ng/kg·bw/day for females (Fig. 2B).

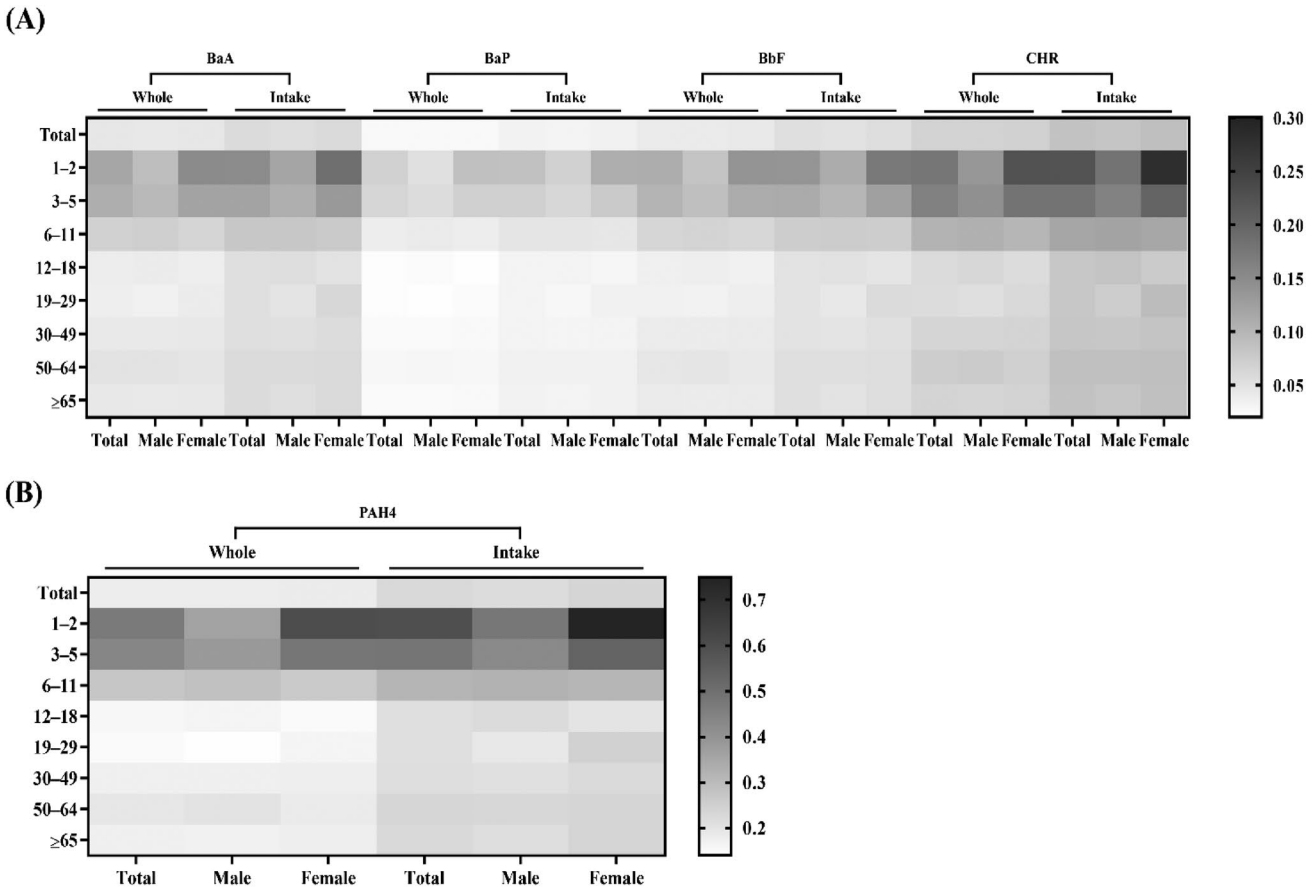


Fig. 2 Heatmap of estimated daily dietary exposure according to consumption pattern. Whole and intake population, generated using Prism 8.0.2. Darker gray indicates higher exposure levels. (**A**) Estimated daily dietary exposure (ng/kg·bw/day) to BaA, BaP, BbF, and CHR according to age and sex group. (**B**) Estimated daily dietary exposure (ng/kg·bw/day) to PAH4 compounds according to age and sex group. *PAH* polycyclic aromatic hydrocarbon, *BaA* benzo[a]anthracene, *BaP* benzo[a]pyrene, *BbF* benzo[b]fluoranthene, *CHR* chrysene

Consistent with previous studies (Kang et al., 2014; Lee et al., 2019), the calculated MOE values in this study exceeded 10,000 in all population groups, suggesting that the overall health risk posed by sesame oil consumption remains low. Studies conducted in Korea have also reported low health risks for edible oils other than sesame oil, with MOE values exceeding 10,000 (Lee et al., 2019). In addition, studies conducted in other regions, such as Iran and Poland, also reported MOE values exceeding 10,000 for edible oils other than sesame oil, suggesting low health risks (Ciecierska and Obiedziński, 2013; Yousefi et al., 2018). However, when stratified by age and sex, MOE values in younger children—particularly those aged 1–5 years—were comparatively lower, reflecting their higher intake relative to body weight. The lowest MOE values were observed for BaP and PAH4 in the 1–2 years age group, indicating a relatively greater vulnerability in this subpopulation.

Similar patterns have been reported in other regions. Martí-Cid et al. (2007) noted that children in Catalonia exhibited higher contaminant intake per kg of body weight, especially for PAH16 compounds. Furthermore, as noted by Mielech et al. (2021), infants and toddlers may be particularly susceptible to foodborne toxicants due to their physiological characteristics, such as higher intake per body weight, increased surface area, and developmental immaturity.

These findings emphasize the need for targeted risk assessment approaches for vulnerable age groups, even in cases where overall population risk appears minimal. Studies on edible oils other than sesame oil have also confirmed that children aged 2–6 years are more vulnerable (Liu et al., 2023), which is consistent with previous research indicating that children are more susceptible to PAH exposure and face a greater risk of developing health problems (EC, 2011).

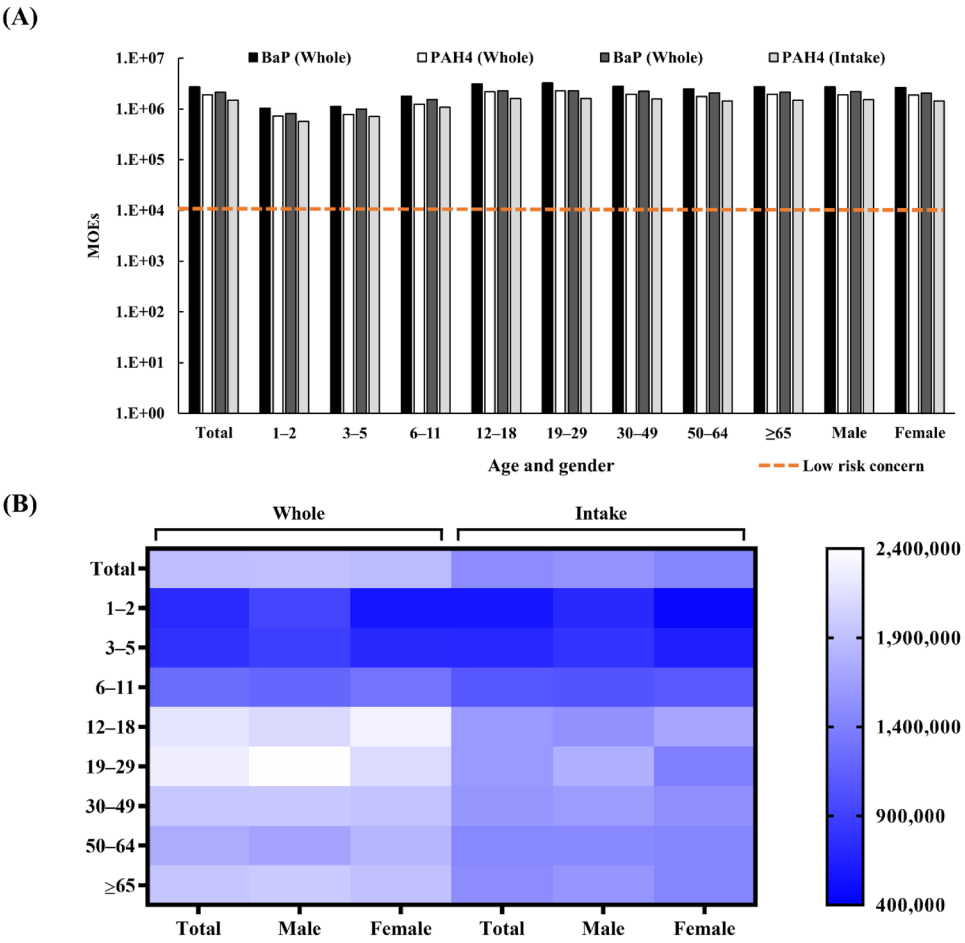


Fig. 3 **(A)** MOE values for BaP and PAH4 compounds based on age and sex group according to consumption patterns (whole and intake population). **(B)** Heatmap of MOE values for BaP and PAH4 compounds according to age and sex group based on consumption patterns, generated using Prism 8.0.2 Darker gray indicates lower MOE values. *MOE* margin of exposure, *PAH* polycyclic aromatic hydrocarbon

Risk characterizations of PAH4 compounds depend on exposure scenarios

The MOE values for BaP and PAH4 were calculated by age and sex groups based on daily dietary exposure, using the $BMDL_{10}$ values as reference points (Fig. 3). Detailed MOE values are presented in Supplementary Table S6, with age-specific graphs for both male and female groups also provided. Since the MOE values were derived by dividing the same exposure values by the $BMDL_{10}$ of BaP and PAH4, they were numerically identical for both compounds. The data were visualized as a heatmap using Prism 8.0.2, where darker blue shades indicate lower MOE values (Fig. 3B).

Across all age and sex groups, MOE values exceeded the threshold of 10,000 (Fig. 3A), indicating low health risks associated with the consumption of the 30 sesame oil products by the South Korean population (EFSA, 2012). Compared with BaP, PAH4 consistently exhibited lower MOE values across all groups, with similar patterns observed in both the general and intake populations (Fig. 3B). Lower MOE values were observed in the 1–2, 3–5, and 6–11 years age groups, with the 1–2 years sex-combined intake population showing the lowest MOE values: 8.11×10^5 for BaP and 5.69×10^5 for PAH4 (Fig. 3B). In contrast, the highest values were observed in the 19–29 years age group: 22.78×10^5 for BaP and 15.98×10^5 for PAH4 (intake population). For the 1–2 years age group, MOE values for PAH4 were 7.10×10^5 for males and 4.56×10^5 for females (Fig. 3B).

Figs. 4A and B illustrate scatter plots depicting the inverse relationship between dietary exposure and MOE values for BaP and PAH4, stratified by age, sex, and consumption group. Supplementary Fig. S3 presents detailed age-specific trends in both male and female groups. As expected from toxicological principles, an inverse correlation was observed—higher exposure was associated with lower MOE values. This finding is consistent with established toxicological principles (Benford, 2016). Because dietary exposure and MOE are inversely correlated, visualization of the data allows for an integrated assessment that can identify relatively high-risk groups, even when all MOE values exceed 10,000 and suggest low overall health risk. These results clearly indicate that the 1–2 and 3–5 years age groups exhibited the highest exposure and lowest MOE values (whole population: blue, intake population: red), identifying them as relatively vulnerable groups. In addition, by comparing the distribution between the whole and

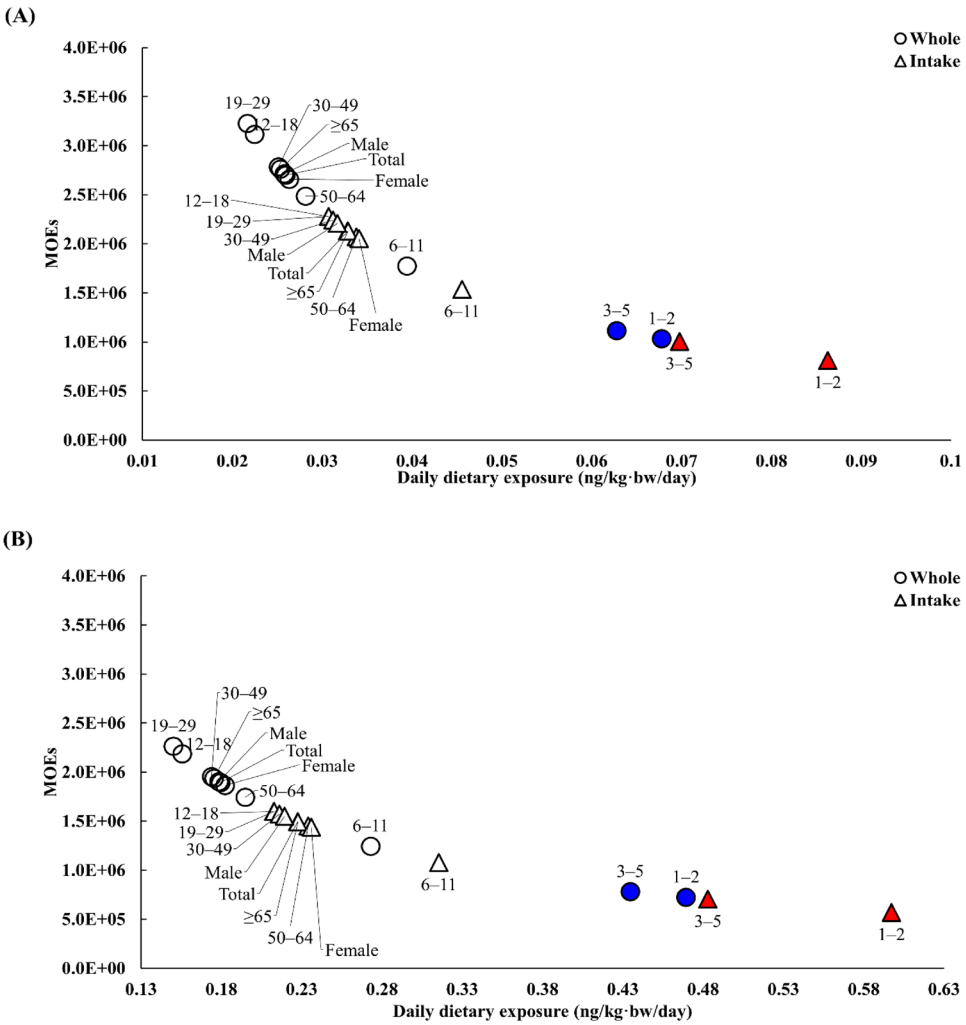


Fig. 4 Inverse relationship between estimated daily dietary exposure and MOE values for (**A**) BaP and (**B**) PAH4 across age and sex groups in both whole and intake populations. *MOE* margin of exposure, *PAH* polycyclic aromatic hydrocarbon

intake populations, scenario-based comparisons can be made within the same age and sex groups. Notably, when comparing differences according to intake status, the gap between the whole and intake populations was greater in the 1–2 years age group than in the 3–5 years age group, indicating that the younger group is more sensitive to the effects of sesame oil consumption.

Regarding sex-specific differences within these high-risk groups, females in the 1–5 years age group exhibited lower MOE values than males (Fig. 4B). This disparity may reflect differences in sesame oil intake levels and body weight. Jung and Kim (2016) noted that girls aged 4–6 years consumed a wider variety of side dishes compared to boys, who were more selective eaters. This finding aligns with the 2022 KHIDI data, which, within this age range, indicated a higher food intake relative to body weight for young girls compared to young boys.This study investigated the levels of PAH4 compounds—BaA, BaP, BbF, and CHR—in South Korean sesame oil products and assessed the potential health risks associated with their consumption. The HPLC-FLD method employed was validated and found to comply with regulatory standards, confirming its suitability for PAH4 monitoring in the food industry. Among the 30 market samples analyzed, the non-detection rates for all four PAHs were below 60.00%. Based on the measured concentrations, daily dietary exposure and MOE values were estimated across different age groups, sexes, and consumption patterns. All calculated MOE values exceeded the threshold of 10,000, suggesting minimal public health concern. However, infants and young children (1–5 years) exhibited relatively lower MOE values, indicating higher susceptibility, with females in this group showing the greatest vulnerability due to differences in intake and body weight.

Overall, this study confirms that PAH4 exposure through sesame oil consumption does not pose a significant health risk to the general Korean population. Its value lies in identifying exposure-sensitive subpopulations through stratified risk assessment by age and sex. Furthermore, the findings underscore the importance of managing PAH4 compounds collectively rather than focusing solely

on BaP, offering critical evidence to support more comprehensive regulatory approaches. This study has several limitations. In particular, the dataset was limited in terms of the number of sesame oil samples analyzed, which may reduce the representativeness of the risk assessment results. Moreover, the study was conducted over a short period, which did not allow for an analysis of temporal trends. Therefore, the findings should be interpreted with caution. Further studies with larger sample sizes, more diverse product types, and longer-term data collection are required to improve the robustness and generalizability of the risk characterization.

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Data availability The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Competing 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.

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