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Health risk assessment of polycyclic aromatic hydrocarbons (PAHs) in coffee-based products: A meta-analysis study and systematic review

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ABSTRACT

Coffee is a well-known beverage in the world, which due to various minerals and vitamins has an important role in health, while multiple sources can contaminate coffee and threaten health. The current study intended to detect polycyclic aromatic hydrocarbons (PAHs) in roasted, bean, blend, instant, and other types of coffee. Considering the databases of Scopus, Google Scholar, PubMed, and Web of Science, the concentration of PAHs in coffee-based products was meta-analyzed. Moreover, health risks in terms of carcinogenic and mutagenic were assessed. According to the findings of 15 articles, the maximum PAH concentrations in roasted, bean, blend, instant, and other coffee were 25.34, 1.70, 62.85, 43.07, and 3.25 μg kg^{-1} were related to acenaphthylene, chrysene, fluorene, pyrene, and chrysene, respectively. Moreover, based on various countries, the highest concentrations of PAHs in coffee products in America (57.21 μg kg-1), Asia (10.89μgkg-1), Europe (19.17 μg kg-1), and Africa (56.9 μg kg-1) were related to pyrene, naphthalene, acenaphthylene, and phenanthrene, respectively. On the other hand, the risk pattern was different in different countries, so periodic monitoring is essential to reduce the risk to the health of PAHs via the consumption of coffee-based products.

1. Introduction

Industrial and household activities carried out during the harvesting and storage phases often result in the pollution of different food items such as tea, vegetable oil, and fruits, with residues of pesticides, mycotoxins, and other harmful environmental substances [1–4]. Coffee, which ranks just after water, is the second most widely consumed non-alcoholic beverage globally. It can be made from either instant powder or roasted coffee beans, both of which play a significant role in its complex flavor profile [5]. Consumers utilize coffee for its distinct qualities such as its unique flavor, taste, and health benefits. There are over 500 genera and more than 6000 species of coffee known worldwide [6]. According to data gathered from the International Coffee Organization (ICO), the largest coffee-producing nations and regions like Brazil, Vietnam, and Colombia exported approximately 129 million 60 kg bags of coffee beans globally during the 2021–2022 period [7]. Coffee contains a range of beneficial nutrients like trigonelline, diterpenes, chlorogenic acids, tannin, and polyphenols, which are bioactive compounds that can help protect the body from various diseases including cardiovascular issues, cancer, Parkinson's, type 2 diabetes, depression, hypertension, and Alzheimer's [8–10]. Coffee serves as a significant provider of essential vitamins and minerals needed daily. Nevertheless, various harmful substances may arise during the coffee production process. Polycyclic aromatic hydrocarbons (PAHs) are toxic compounds that are neurotoxic, carcinogenic, and genotoxic. These compounds are generated due to the inefficient burning of organic materials (such as coal, oil, gas, wood, and waste) found in the environment, originating from both natural sources (air, soil, and water) and

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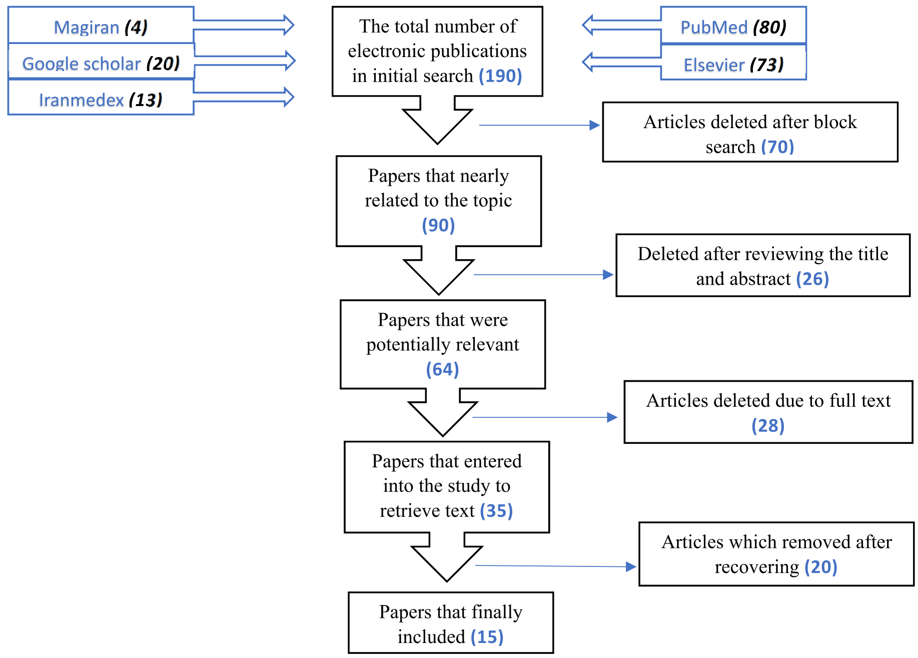

Fig. 1. The flow diagram of included/excluded studies for meta-analysis of the PAHs in Coffee-based Products.

human activities (such as high-temperature cooking during food preparation). Depending on the number of aromatic rings they possess. Polycyclic aromatic hydrocarbons (PAHs) are classified into two categories: light compounds, which consist of 2–3 rings, and heavy compounds, comprising 4 to 6 rings. Individuals may be exposed to PAHs through various routes, including inhalation, dermal contact, and ingestion, as these substances are found within the food web of the ecosystem and can be present in water, air, and soil. The International Agency for Research on Cancer (IARC) has classified benzo(a)pyrene as a Group 1 carcinogen for humans [11]. The Joint FAO/WHO Expert Committee on Food Additives (JECFA) concluded that 16 of the 33 polycyclic aromatic hydrocarbons (PAHs) are both carcinogenic and genotoxic to human health [12]. The roasting of coffee beans is the primary element contributing to the presence of PAHs in the finished product, and this process is influenced by the specific species or cultivar of the coffee beans as well as the roasting conditions [13]. Prior studies have documented the existence of PAHs and various contaminants in certain items [14–16]. The assessment of PAHs in food products and human eating patterns is crucial due to their quick presence in food sources. A meta-analysis can effectively illustrate the different concentrations of different PAHs in coffee worldwide. The current study was carried out to evaluate the concentrations of PAHs in various varieties of coffee, as well as evaluate their potential carcinogenic and mutagenic risks. The outcomes of our study could offer valuable insights into monitoring the presence of PAHs in coffee and identifying any possible gaps in contamination.

2. Method

2.1. Method of study

The systematic review and meta-analysis were conducted to assess the content of PAHs in various coffee products, including roasted, bean, blend, instant, and other types. The research adhered to the protocols detailed in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA), as shown in Fig. 1 [17]. All English-language papers published between May 20, 2004, and June 18, 2023, were acquired utilizing a range of databases such as Web of Science, Google Scholar, Scopus, and PubMed1. Additionally, the bibliographies of chosen papers were reviewed manually to identify supplementary publications. According to the Medical Subject Headings (MeSH), terms were investigated in the title, abstract, and keywords including "polycyclic aromatic hydrocarbons" or "PAHs", and "Food" or "coffee" or "roasted" or "bean" or "instant" or "Bran" or "other coffee" or contaminants, residual, and concentration.

2.2. Inclusive and exclusive criteria, along with data extraction

FM and ET, two researchers, evaluated all articles separately by analyzing their titles, abstracts, and full text according to the inclusion and exclusion criteria. The third author has indicated their agreement concerning the inconsistencies observed in the manuscripts among the researchers. The articles that were chosen were based on the specified criteria, which involved: (1) full-text article accessibility, (2) cross-sectional study methodology, and (3) reporting the mean and standard deviation of PAHs in coffee [18–20]. The study excluded all forms of literature, such as books, duplicates, case reports, clinical trials, review articles, letters to editors, and research on different ways of treatment to remove PAHs from coffee. Additionally, we excluded articles without author attribution, averages, and deviations from the mean, yearly figures, countries, and coffee brands from the analysis. The dataset contained various details, such as the year, location, variety of coffee; number of samples, mean, and variance are included. To ensure consistency in the studies, all measurements of PAHs, consisting of Parts per billion (ppb), nanogram per gram, and microgram per kilogram, were converted to milligrams per kilogram.

2.3. Meta-analysis

The estimation of PAH concentration in products made from coffee utilized the mean and standard error (SE). The standard error was derived from the specified Equation.

$$SE = SD/\sqrt{N} \quad (1)$$

Within this formula, N represents the dimensions of the sample while SD stands for standard deviation [21]. The combined levels of PAHs in coffee items were assessed through the utilization of a model of stochastic impact. The examination of subgroups was conducted

Table 1
Table 1. Meta-analysis of concentration of polycyclic aromatic hydrocarbons (PAHs) in Coffee based on the type of Coffee.

PAH	Coffee	N of studies	ES (95 % CI)	Heterogeneity				
				Weight (%)	Statistics	df	*P*-value	I^2 (%)
Acenaphthene	Roasted Coffee	2	6.08 (−5.5, 17.67)	13.63	2375.55	1	<0.001	100
	Bean Coffee	2	0.098 (−0.04, 0.235)	14.09	540.54	1	<0.001	99.8
	Blend Coffee	4	17.033 (11.05, 23.01)	25.19	1696.3	3	<0.001	99.8
	Instant Coffee	1	0.030 (0.026, 0.034)	7.05	–	–	–	–
	Other Coffee	6	0.031 (0.012, 0.050)	40.04	389.2	5	<0.001	98.7
	Total	15	5.64 (5.17, 6.12)	100.0	1.9e+06	14	<0.001	100.0
Acenaphthylene	Roasted Coffee	3	25.34 (−4.98, 55.66)	19.29	28696.77	2	<0.001	100.0
	Bean Coffee	1	0.076 (0.071, 0.081)	10.98	–	–	–	–
	Blend Coffee	4	35.048 (15.999, 54.098)	10.93	644.79	3	<0.001	99.5
	Instant Coffee	2	38.86 (−37.28, 115.01)	12.35	13885.86	1	<0.001	100.0
	Other Coffee	5	0.027 (0.018, 0.036)	46.45	89.69	4	<0.001	95.5
	Total	15	6.313 (6.151, 6.474)	100.0	1.3e+05	14	<0.001	100.0
Anthracene	Roasted Coffee	4	1.19 (1.09, 1.28)	24.29	11117.2	3	<0.001	100.0
	Bean Coffee	1	0.007 (0.007, 0.007)	11.82	–	–	–	–
	Blend Coffee	4	12.05 (5.92, 18.17)	1.7	2085.19	3	<0.001	99.9
	Instant Coffee	2	5.45 (−5.2, 16.09)	13.78	13433.2	1	<0.001	100.0
	Other Coffee	7	0.045 (0.022, 0.068)	48.40	729.3	6	<0.001	99.2
	Total	18	0.498 (0.47, 0.526)	100.0	31713.21	17	<0.001	99.9
Benzo [a] anthracene	Roasted Coffee	3	6.85 (5.81, 7.88)	16.7	3189.74	2	<0.001	99.9
	Bean Coffee	2	0.047 (−0.031, 0.125)	17.82	31939.24	1	<0.001	100.0
	Blend Coffee	5	5.05 (−0.66, 10.76)	15.15	30003.44	4	<0.001	100.0
	Instant Coffee	2	3.09 (−2.93, 9.11)	14.65	22783.51	1	<0.001	100.0
	Other Coffee	7	0.029 (0.015, 0.044)	35.67	291.37	6	<0.001	97.9
	Total	19	0.977 (0.945, 1.009)	100.0	92228.13	18	<0.001	100.0
Benzo [a] pyrene	Roasted Coffee	23	3.69 (3.1, 4.29)	56.21	24886.91	22	<0.001	99.9
	Bean Coffee	1	0.125 (0.124, 0.126)	–	–	–	–	–
	Blend Coffee	5	6.16 (−0.65, 12.97)	12.73	23781.98	4	<0.001	100.0
	Instant Coffee	4	6.99 (4.42, 9.56)	11.06	2485.82	3	<0.001	99.9
	Other Coffee	7	5.42 (4.04, 6.81)	16.33	2656.20	6	<0.001	99.8
	Total	40	3.52 (3.42, 3.63)	100.0	78959.05	39	<0.001	100.0
Benzo [b]flouranthene	Roasted Coffee	5	2.80 (2.52, 3.08)	9.41	4004.59	4	<0.001	99.9
	Bean Coffee	4	0.057(0.035, 0.078)	18.31	8109.94	3	<0.001	100.0
	Blend Coffee	5	1.69 (0.611, 2.763)	9.14	1942.03	4	<0.001	99.8
	Instant Coffee	5	2.30 (2.10, 2.51)	17.46	22943.01	4	<0.001	100.0
	Other Coffee	12	0.021 (0.017, 0.025)	45.68	296.02	11	<0.001	96.3
	Total	31	0.353 (0.332, 0.373)	100.0	90358.97	30	<0.001	100.0
Benzo(g,h,i)perylene	Blend Coffee	2	4.07 (−0.38, 8.53)	52.83	147.66	1	<0.001	99.3
	Other Coffee	2	26.66 (−37.71, 90.70)	47.17	499.94	1	<0.001	99.8
	Total	4	13.18 (8.66, 17.72)	100.0	1163.91	3	<0.001	99.7
Benzo [k]fluoranthene	Roasted Coffee	4	0.014 (−0.002, 0.03)	35.91	2217.02	3	<0.001	99.9
	Blend Coffee	5	15.96 (7.04, 24.88)	18.39	6386.53	4	<0.001	99.9
	Instant Coffee	2	4.13 (−0.83, 9.09)	10.64	3807.76	1	<0.001	100.0
	Other Coffee	3	0.05 (−0.03, 0.131)	35.07	112.38	2	<0.001	98.2
	Total	14	0.613 (0.582, 0.644)	100.0	24441.98	13	<0.001	99.9
Chrysene	Roasted Coffee	2	17.54 (−15.49, 50.58)	10.75	7942.76	1	<0.001	100.0
	Bean Coffee	2	1.79 (−1.39, 4.98)	18.13	3.7e+05	1	<0.001	100.0
	Blend Coffee	6	2.79 (2.51, 3.07)	20.04	4364.62	5	<0.001	99.9
	Instant Coffee	3	10.19 (6.79, 13.58)	16.59	1987.31	2	<0.001	99.9
	Other Coffee	6	3.25 (1.92, 4.58)	34.48	3015.18	5	<0.001	99.8
	Total	19	2.95 (2.83, 3.06)	100.0	4.6e+05	18	<0.001	100.0
Dibenz[a,h]anthracene	Roasted Coffee	2	7.82 (−7.22, 22.86)	11.12	303.78	1	<0.001	99.7
	Bean Coffee	2	0.006 (0.004, 0.008)	22.25	43.24	1	<0.001	97.7
	Blend Coffee	5	18.30 (10.20, 26.41)	10.44	5083.71	4	<0.001	99.9
	Instant Coffee	2	2.62 (−2.48, 7.72)	11.74	4904.87	1	<0.001	100.0
	Other Coffee	4	0.016 (0.008, 0.024)	44.46	584.61	3	<0.001	99.5
	Total	15	0.082 (0.07, 0.094)	100.0	14310.49	14	<0.001	99.9
Flouranthene	Roasted Coffee	3	1.15 (0.98, 1.31)	20.51	2210.03	2	<0.001	99.9
	Bean Coffee	2	0.023 (−0.014, 0.06)	14.96	648.99	1	<0.001	99.8
	Blend Coffee	4	26.58 (11.72, 41.44)	20.95	51378.71	3	<0.001	100.0
	Instant Coffee	1	2.88 (2.70, 3.06)	7.16	–	–	–	–
	Other Coffee	7	7.37 (5.84, 8.90)	36.43	5318.48	6	<0.001	99.9
	Total	17	6.76 (6.53, 6.99)	100.0	2.7e+05	16	<0.001	100.0
Fluorene	Roasted Coffee	5	14.61 (13.67, 15.55)	27.89	17307.14	4	<0.001	100.0
	Bean Coffee	2	0.15 (−0.01, 0.315)	16.06	378.12	1	<0.001	99.7
	Blend Coffee	4	62.85 (38.03, 87.67)	7.6	1947.99	3	<0.001	99.8
	Instant Coffee	3	23.93 (7.84, 40.02)	15.72	13005.95	2	<0.001	100.0
	Other Coffee	5	0.029 (0.017, 0.041)	37.72	185.72	4	<0.001	97.8
	Total	19	9.87 (9.69, 10.05)	100.0	2.3e+05	18	<0.001	100.0
Indeno (l,2,3-c,d) pyrene	Roasted Coffee	3	4.16 (−3.56, 11.87)	19.23	1.5e+06	2	<0.001	100.0
	Bean Coffee	3	0.11 (0.06, 0.16)	19.23	1304.51	2	<0.001	99.8
	Blend Coffee	5	20.59 (11.91, 29.28)	12.71	1650.59	4	<0.001	99.8
	Instant Coffee	2	4.48 (−4.24, 13.20)	12.7	15839.22	1	<0.001	100.0
	Other Coffee	8	0.05 (0.03, 0.08)	36.13	1689.32	7	<0.001	99.6

(*continued on next page*)

Table 1 (*continued*)

PAH	Coffee	N of studies	ES (95 % CI)	Heterogeneity				
				Weight (%)	Statistics	df	*P*-value	I^2 (%)
	Total	21	2.98 (2.73, 3.23)	100.0	1.9e+06	20	<0.001	100.0
Naphthalene	Roasted Coffee	3	11.89 (8.11, 15.68)	20.49	9928.83	2	<0.001	100.0
	Bean Coffee	2	0.52 (0.40, 0.63)	13.66	21.18	1	<0.001	95.3
	Blend Coffee	4	48.06 (−14.69, 110.81)	25.02	73616.17	3	<0.001	100.0
	Instant Coffee	1	6.59 (6.28, 6.89)	6.83	–	–	–	–
	Other Coffee	5	10.24 (8.4412.03)	33.99	355.96	4	<0.001	98.9
	Total	15	19.66 (13.94, 25.38)	100.0	7.0e+05	14	<0.001	100.0
Phenanthrene	Roasted Coffee	4	13.96 (12.51, 15.42)	21.06	8189.87	3	<0.001	100.0
	Bean Coffee	2	0.092 (0.082, 0.102)	18.06	4.71	1	0.030	78.8
	Blend Coffee	4	5.76 (3.83, 7.68)	14.55	350.60	3	<0.001	99.1
	Instant Coffee	2	18.0 (−17.23, 53.25)	9.29	1590.91	1	<0.001	99.9
	Other Coffee	7	0.12 (0.066, 0.174)	37.04	936.27	6	<0.001	99.4
	Total	19	1.67 (1.58, 1.76)	100.0	16310.95	18	<0.001	99.9
Pyrene	Roasted Coffee	4	0.137 (0.093, 0.181)	18.36	3382.91	3	<0.001	99.9
	Bean Coffee	2	0.016 (0.014, 0.018)	18.09	6.23	1	0.013	83.9
	Blend Coffee	4	41.47 (20.43, 62.52)	0.03	181.25	3	<0.001	98.3
	Instant Coffee	3	43.07 (31.09, 55.06)	9.69	10809.81	2	<0.001	100.0
	Other Coffee	8	0.032 (0.013, 0.05)	53.84	842.04	7	<0.001	99.2
	Total	21	0.167 (0.143, 0.191)	100.0	20819.28	20	<0.001	99.9
1-Methylnaphthalene	Blend Coffee	6	46.55 (−3.47, 96.58)	100.0	8.0e+05	5	<0.001	100.0
	Total	6	46.55 (−3.47, 96.58)	100.0	8.0e+05	5	<0.001	100.0

independently according to the variety of coffee and the nation of production. An analysis using the chi-square test was performed to identify diversity. The diversity of the meta-analysis was evaluated through Q and I^2 examinations. The Cochran Q test (Q statistic, $p < 0.10$) and I2 statistic (I2 > 50 %) indicated significant diversity and substantial heterogeneity, respectively. The data were analyzed using Stata software, version 11 (Stata Corp, College Station, TX, USA). A significance level of $p < 0.05$ was deemed significant.

2.4. Risk evaluation

The estimation of mutagenic and carcinogenic hazards associated with 7 PAH compounds in coffee products were conducted by the BaP equivalent dose of mutagenic or carcinogenic PAHs (BaPEQ). The BaPEQ value relies on the toxicity equivalent quotient (TEQ BaP) or (MEQ BaP), which is determined by multiplying the sum of the mutagenic equivalent factor (MEF) or toxicity equivalent factor (TEF) by each PAH concentration. TEQ BaP or MEQ BaP and also BaPEQ were calculated using the following equations (2) and (3):

$$TEQBaP = \sum (TEFi \times Ci) \tag{2}$$

$$MEQBaP = \sum (MEF\ i \times Ci) \tag{3}$$

The concentration of individual PAHs, Ci, corresponds to the following TEFi values: BaA (0.1), BaP (1), BbFlu (0.1), BkFlu (0.01), Chr (0.001), DahA (1), and IndP (0.1). The MEFi values for BaA, BaP, BbFlu, BkFlu, Chr, DahA, and IndP were 0.082, 1, 0.25, 0.11, 0.017, 0.290, and 0.310, in that order. The equivalent dose of BaP was determined using the subsequent formula [15].

$$BaPEQ = (TEQ\ or\ MEQ) \times IR \times EF \times ED / BW \times AT \tag{4}$$

Based on equation (4), IR is the intake pace of coffee (mg day-1) which was presented in Table 3 and illustrates the per capita cereals consumption for each country, EF denotes the frequency of exposure (350 days per year), ED stands for the duration of exposure (30 years for adults), BW represents body weight (70 kg for adults), and ATn (EF × ED) signifies the average time of exposure (10,950 days for adults). The calculation of mutagenic or cancer risk was determined utilizing the specified equation [22].

(5)The potential for developing cancer or mutations can be calculated by multiplying the BaP equivalent dose of a mixture of PAHs by the SFBaP factor.

SFBaP denotes the slope factor for benzo[a]pyrene, a substance known to be carcinogenic when consumed orally at a rate of 7.30 mg/kg per day. According to USEPA recommendations, the risk of developing cancer (CR) exceeding 10-4 signifies risk; CR falling between 10-6 to 10-4 is deemed Satisfactory; and CR below 10-6 Signifies security [23].

3. Results and discussion

3.1. Study processing and its features

The analysis carried out in this research is illustrated in Fig. 1. The present study encompassed the collection of 160 published articles from May 20, 2004, to June 18, 2023, obtained via searches conducted in major databases. At the outset, Duplicate content led to the exclusion of 70 articles from the study. The titles of 90 articles were considered suitable. 26 articles were deemed unsuitable for analysis due to their titles, resulting in the exclusion. A total of 64 articles were examined based on their abstracts, leading to the exclusion of 28 articles. A total of 35 articles were reviewed, of which 20 were excluded because their texts were incomplete. Ultimately, the study focused on the full texts of 15 articles. These studies are including [24–36]. Table 1 displays the primary attributes of studies gathered globally. The study regions were categorized in the following order: Europe (33 %), Africa (0.06 %), America (13 %), and Asia (46 %).

3.2. The concentration of various PAHs in coffee products

The findings from the present investigation revealed significant variability among the polycyclic aromatic hydrocarbons (PAHs) found in coffee-related products, including roasted, bean, blend, instant, and other forms of coffee. The determination was made using Cochran's Q test and I2 statistics, resulting in a Q value of 1037.26, 307 degrees of freedom (df), and a p-value of less than 0.001. Additionally, the I2 statistic indicated heterogeneity of 100 %. Consequently, to mitigate this heterogeneity, subgroup analyses were conducted based on the types of coffee and the countries of origin (Tables 1 and 2). The outcomes obtained show that the PAH concentrations in various coffee types, including roasted, bean, blend, instant, and others, were measured at 25.34, 1.70, 62.85, 43.07, and 3.25 μg kg-1, in the order mentioned, as presented in Table 1. The concentrations were associated with acenaphthylene, chrysene, fluorene, pyrene, and chrysene, in that order. The roasted, bean, blend, instant, and other varieties of coffee displayed differing concentrations of PAHs. Specifically, the lowest levels detected

Table 2
Meta-analysis of concentration of toxic metal (PTEs) (μg.kg) in Coffee based on the continents.

PAH	Continent	N of studies	ES (95 % CI)	Heterogeneity				
				Weight (%)	Statistics	df	*P*-value	I^2 (%)
Acenaphthene	America	4	17.03 (11.05, 23.01)	25.19	1696.33	3	<0.001	99.8
	Asia	6	0.184 (0.132, 0.237)	39.99	2530.44	5	<0.001	99.8
	Europe	5	0.115 (0.07, 0.156)	34.82	1477.33	4	<0.001	99.7
	Total	15	5.64 (5.17, 6.12)	100.0	1.9e+06	14	<0.001	100.0
Acenaphthylene	America	4	35.05 (15.99, 54.09)	10.93	644.79	3	<0.001	99.5
	Asia	6	0.248 (0.192, 0.304)	51.13	6348.9	5	<0.001	99.9
	Europe	5	19.17 (18.52, 19.82)	37.95	36493.78	4	<0.001	100.0
	Total	15	6.31 (6.15, 6.48)	100.0	1.3e+05	14	<0.001	100.0
Anthracene	Africa	1	16.7 (15.24, 18.16)	0.04	–	–	–	–
	America	4	12.05 (5.92, 18.17)	1.7	2085.19	3	<0.001	99.9
	Asia	6	0.34 (0.279, 0.393)	47.76	6651.94	5	<0.001	99.9
	Europe	7	0.438 (0.404, 0.473)	50.50	18272.92	6	<0.001	100.0
	Total	18	0.498 (0.47, 0.53)	100.0	31713.21	17	<0.001	99.9
Benzo [a] anthracene	America	4	6.30 1.78, 10.83)	6.24	3524.48	3	<0.001	99.9
	Asia	9	0.105 (0.082, 0.128)	61.23	12258.58	8	<0.001	99.9
	Europe	6	1.34 (1.27, 1.41)	32.53	25449.48	5	<0.001	100.0
	Total	19	0.977 (0.945, 1.009)	32.53	92228.13	18	<0.001	100.0
Benzo [a] pyrene	Africa	1	19.2 (17.52, 20.88)	0.36	–	–	–	–
	America	23	3.75 (2.11, 5.39)	52.42	21920.48	22	<0.001	99.9
	Asia	10	6.16 (−0.65, 12.97)	12.73	16680.34	9	<0.001	99.9
	Europe	6	7.22 (6.27, 8.16)	17.4	27140.80	5	<0.001	100.0
	Total	40	3.52 (3.42, 3.63)	100.0	78959.05	39	<0.001	100.0
Benzo [b]flouranthene	America	4	2.084 (0.67, 3.49)	4.61	856.46	3	<0.001	99.6
	Asia	18	0.042 (0.023, 0.062)	68.73	50720.25	17	<0.001	100.0
	Europe	9	1.69 (1.60, 1.77)	26.66	27590.13	8	<0.001	100.0
	Total	31	0.353 (0.332, 0.373)	100.0	90358.97	30	<0.001	100.0
Benzo(g,h,i)perylene	Africa	1	53.4 (48.72, 58.08)	20.66	–	–	–	–
	America	2	4.08 (−0.383, 8.535)	52.83	147.66	1	<0.001	99.3
	Europe	1	0.003 (0.002, 0.004)	26.51	–	–	–	–
	Total	4	13.19 (8.66, 17.72)	100.0	1163.91	3	<0.001	99.7
Benzo [k]fluoranthene	America	5	16.27 (8.11, 24.42)	5.69	4953.32	4	<0.001	99.9
	Asia	3	9.13 (−6.50, 24.77)	17.65	459.87	2	<0.001	99.6
	Europe	6	0.43 (0.401, 0.468)	76.66	16613.30	5	<0.001	100.0
	Total	14	0.613 (0.582, 0.644)	100.0	24441.98	13	<0.001	99.9
Chrysene	America	5	31.23 (25.73, 36.74)	2.16	55.44	4	<0.001	92.8
	Asia	11	1.52 (1.39, 1.65)	78.47	4.4e+05	10	<0.001	100.0
	Europe	3	13.54 (7.06, 20.02)	19.38	19439.66	2	<0.001	100.0
	Total	19	2.95 (2.83, 3.07)	100.0	4.6e+05	18	<0.001	100.0
Dibenz[a,h]anthracene	America	4	22.87 (13.61, 32.13)	0.11	715.81	3	<0.001	99.6
	Asia	5	0.056 (0.044, 0.069)	54.78	1573.36	4	<0.001	99.7
	Europe	6	0.052 (0.039, 0.066)	45.11	5651.48	5	<0.001	99.9
	Total	15	0.082 (0.070, 0.094)	100.0	14310.49	14	<0.001	99.9
Flouranthene	Africa	1	44.4 (40.51, 48.29)	0.33	–	–	–	–
	America	4	26.58 (11.72, 41.44)	20.95	51378.71	3	<0.001	100.0
	Asia	6	5.96 (4.60, 7.31)	36.99	1695.90	5	<0.001	99.7
	Europe	6	0.063 (0.029, 0.098)	41.73	2243.36	5	<0.001	99.8
	Total	17	6.76 (6.53, 6.99)	100.0	2.7e+05	16	<0.001	100.0
Fluorene	America	5	52.86 (15.78, 89.94)	13.71	62182.25	4	<0.001	100.0
	Asia	7	0.702 (0.631, 0.773)	42.55	10470.05	6	<0.001	99.9
	Europe	7	5.85 (5.52, 6.18)	43.74	16131.87	6	<0.001	100.0
	Total	19	9.87 (9.69, 10.05)	100.0	2.3e+05	18	<0.001	100.0
Indeno (l,2,3-c,d) pyrene	Africa	1	38.7 (35.31, 42.09)	0.49	–	–	–	–
	America	4	25.91 (16.13, 35.68)	6.30	284.57	3	<0.001	98.9
	Asia	8	0.087 (0.044, 0.13)	42.27	18200.52	7	<0.001	100.0
	Europe	8	2.84 (1.56, 4.12)	50.94	1.8e+06	7	<0.001	100.0
	Total	21	2.98 (2.73, 3.23)	100.0	1.9e+06	20	<0.001	100.0
Naphthalene	Africa	1	38.9 (35.49, 42.31)	6.67	–	–	–	–
	America	4	48.06 (−14.69, 110.81)	25.02	73616.17	3	<0.001	100.0
	Asia	6	10.89 (5.47, 16.31)	40.97	6636.75	5	<0.001	99.9
	Europe	4	0.73 (0.50, 0.97)	27.33	297.98	3	<0.001	99.9
	Total	15	19.66 (13.94, 25.38)	100.0	7.0e+05	14	<0.001	100.0
Phenanthrene	Africa	1	56.9 (51.91, 61.89)	0.03	–	–	–	–
	America	4	5.76 (3.83, 7.69)	14.55	350.60	3	0.030	99.1
	Asia	6	0.964 (0.857, 1.07)	40.13	6091.84	5	<0.001	99.9
	Europe	8	1.25 (1.06, 1.44)	45.29	5358.93	7	<0.001	99.9
	Total	19	1.67 (1.58, 1.76)	100.0	16310.95	18	<0.001	99.9
Pyrene	Africa	1	37.1 (33.85, 40.35)	0.01	–	–	–	–
	America	5	57.21 (26.28, 88.15)	0.03	863.04	4	<0.001	99.5
	Asia	6	0.085 (0.046, 0.124)	36.32	1371.32	5	<0.001	99.6
	Europe	9	0.115 (0.092, 0.137)	63.64	10349.17	8	<0.001	99.9
	Total	21	0.167 (0.143, 0.191)	100.0	20819.3	20	<0.001	99.9
1-Methylnaphthalene	America	6	46.55 (−3.47, 96.58)	100.0	8.0e+05	5	<0.001	100.0
	Total	6	46.55 (−3.47, 96.58)	100.0	8.0e+05	5	<0.001	100.0

Table 3
Carcinogenic risk assessment of PAHs in Coffee based on BaP equivalency.

Country	IR(kg)	BaA	BaP	BbFlu	BkFlu	Chr	DahA	IndP	Total
Brazil	1.94	–	7.44E-02	–	–	–	–	–	7.44E-02
Denmark	8.7	–	5.22E-01	–	–	–	–	–	5.22E-01
India	0.01	6.78E-05	6.71E-04	1.23E-05	2.60E-06	6.44E-07	–	1.66E-04	9.20E-04
Iran	0.03	1.04E-04	3.63E-03	9.99E-05	–	2.10E-06	8.22E-06	3.68E-04	4.21E-03
Italy	4.7	3.41E-04	7.73E-04	4.51E-05	5.15E-06	3.28E-06	2.58E-04	6.44E-05	1.49E-03
Japan	1.5	–	2.82E-01	–	–	–	–	–	2.82E-01
Korea	0.027	1.04E-05	5.14E-05	2.22E-05	4.72E-05	3.29E-07	8.14E-05	3.83E-06	2.17E-04
Nigeria	0.04	–	1.05E-02	–	–	–	–	4.40E-04	1.10E-02
Poland	2.25	4.72E-02	4.90E-01	3.60E-02	4.30E-03	6.27E-04	3.22E-01	3.23E-02	9.33E-01
Romania	1.9	5.02E-03	–	1.68E-04	9.11E-06	–	2.60E-04	9.11E-04	6.37E-03
USA	4.71	4.06E-02	4.73E-01	1.35E-02	1.05E-02	2.22E-03	1.48E+00	1.73E-01	2.19E+00
Total		9.34E-02	1.86E+00	4.98E-02	1.49E-02	2.85E-03	1.80E+00	2.07E-01	4.03E+00

Chr = chrysen, BaA = benzo[a]anthracene, BaP = benzo[a]pyrene, BkF = benzo [k]fluoranthene, BbF = benzo[b] fluranthene BghiP = benzo[g,h,i]perylene, DahA = dibenz[a,h]anthracene, IndP = indeno[1,2,3,c,d]pyrene.

were 0.014, 0.006, 1.61, 0.030, and 0.016 μg kg-1, respectively. These levels were linked to benzo[k]fluoranthene, dibenz[a,h]anthracene, benzo[b]flouranthene, acenaphthene, and dibenz[a,h]anthracene, respectively. The findings specified a notable difference in the presence of PAH types in coffee-infused items ($p < 0.05$). The outcomes of this research were consistent with earlier investigations. For instance, Iwegbue CM et al. (2015) reported average concentrations of 16 PAHs in coffee ranging from 38.7 to 593.1, respectively [37]. In the study conducted by Grover and associates in 2013, 13 polycyclic aromatic hydrocarbons (PAHs) were detected in four distinct brands of ground coffee. The measured concentrations of these PAHs varied between 831.7 and 1589.7 μg kg−1 [38]. Lee and Shin (2010) discovered in a different research that the levels of PAHs in ten coffee samples varied from 0.62 to 53.25 μg kg−1 [39]. Orecchio and colleagues (2009) showed that the levels of PAHs in brewed coffee varied from 0.52 to 1.825 μg kg−1 [40]. A study conducted by Bishnoi et al., in 2005 revealed that the total concentrations of PAHs in various coffee brands ranged from 16.47 to 18.24 μg l−1 [25]. According to a study conducted by Stanciu et al., in 2008, it was reported that the levels of PAHs in samples of coffee ranged from 0.001 to 90.732μgkg−1 [41]. The PAH content observed in our research differed from that of previous studies. Several factors could account for this variation, including the basic components employed in cooking, increasing the temperature levels during the drying process, potential additional contamination from devices and packaging, storage conditions, the conditions under which coffee beans are cultivated and stored, and various processing techniques involve drying, smoking, grilling, frying, roasting, and baking. In 2015, Sadowska-Rociek and colleagues found that the levels of PAHs in instant coffee were 343, and roasted coffee was 364 μgkg−1. The research indicated that the concentrations of five-ring heavy polycyclic aromatic hydrocarbons (PAHs) in roasted coffee were significantly higher than those found in instant coffee, likely attributable to variations in the production processes. As a result, the infusion of hot water with roasted coffee to enhance its taste and scent may lead to a higher likelihood of light PAHs being transferred into the coffee [42]. The incidence of high levels of PAH in coffee can be associated with various physicochemical properties, including solubility in water and fat, variability, chemical reactivity, the degradability of both biotic and abiotic substances, and hydrophobic characteristics. Chawda et al. suggest that directly burning coal for coffee roasting may play a role in the increased presence of five heavy PAHs in coffee. Burning coal can result in the retention of PAHs containing over five rings and high molecular weight in the solid state, which could present a notable health risk to individuals [43]. Roudbari and colleagues (2021) found that the average concentration of PAHs in coffee samples was 13.75 ± 2.90 μg kg−1. Their study revealed that changes in storage conditions, such as heightened molecular interactions, fluctuations in temperature and moisture levels, and also exposure to sunlight, significantly impact the levels of PAHs in the products [44]. The kind of energy utilized for heating, and the approach employed by the food processor can potentially impact the PAH level in the specific type of food [45]. Orecchio and colleagues showed that the presence of PAHs in coffee samples is linked to the coffee roasting process, which includes a very high-temperature treatment. This treatment can be carried out through direct methods such as roasting over an open flame, grilling with coal, or using a gas oven for toasting, as well as through an indirect method like electric oven-toasting [46].

3.3. PAH concentrations in coffee products differ depending on the country of origin

Variations in the levels of PAHs were observed in product samples of coffee across different countries, as indicated by the findings of this study. Refer to Table 2 for further details; the highest concentration of PAHs in coffee products in American counties was 57.21, and the lowest concentration was 2.084 μg kg-1, which were related to pyrene and benzo [b] fluoranthene respectively. In Asia, naphthalene (10.89μgkg-1) and benzo [b] fluoranthene (0.042 μg kg-1) had the most elevated and lowest levels of PAHs in coffee products. In Europe, it was found that the highest (19.17 μg kg-1) and lowest (0.003 μg kg-1) concentrations of PAHs in coffee products were related to acenaphthylene and benzo (g, h, i) perylene. Phenanthrene and anthracene had the highest (56.9 μg kg-1) and lowest (16.7 μg kg-1) concentrations of PAHs in coffee products of African countries. The current meta-analysis findings indicated a notable disparity ($P < 0.05$) in the PAH content across different global regions. The levels of PAHs in coffee products were evaluated in diverse nations. In Romania, Muntean and colleagues (2013) conducted a study on the levels of PAH in coffee from Romania. The amounts of acenaphthene, phenanthrene, anthracene, fluoranthene, and pyrene were 2.66, 12.84, 1.40, 4.23, and 0.02 μg kg-1, respectively [47]. The quantity of acenaphthylene, acenaphthene, fluorine, phenanthrene, and anthracene in coffee samples from Italy was found to be 0.088, 0.009, 0.073, 0.220, and 0.044 μg kg⁻, correspondingly. In a similar vein, Kamalabadi et al. (2018) found that the average concentrations of benzo (c) fluorene, benzo [a] anthracene, chrysene, and 5-methyl chrysene in the Iranian coffee samples were 318.7, 12.57, 16.5, and 12.27 μg kg-1, respectively [36]. In a study conducted by Lee et al. (2010), it was found that the mean concentration of benzo [a] anthracene was 0.70 μg kg-1, chrysene was 0.68 μg kg-1, benzo [b] fluoranthene was 2.13 μg kg-1, and benzo [k] fluoranthene was 25.46 μg kg-1 in Korean samples [35]. The presence of PAH contamination in coffees from various countries is a direct result of the environmental conditions in which the coffee is grown such as pollution of the atmosphere, plants, soil, and water. Additionally, various industries, operating mines, pollution in urban and rural areas, as well as food processing and cooking techniques are all factors that can lead to PAH contamination [48,49]. The geographical locations and climate of each area significantly impact the levels of PAH found in products. Girelli and colleagues have shown that

Table 4
Mutagenic risk assessment based on BaP equivalency for consumption Coffee.

Country	BaA	BaP	BbFlu	BkFlu	Chr	DahA	IndP	Total
Brazil	–	7.44E-02	–	–	–	–	–	7.44E-02
Denmark	–	5.22E-01	–	–	–	–	–	5.22E-01
India	5.56E-05	6.71E-04	3.08E-05	2.86E-05	1.09E-05	–	5.14E-04	1.31E-03
Iran	8.53E-05	3.63E-03	2.50E-04		3.57E-05	2.38E-06	1.14E-03	5.15E-03
Italy	2.80E-04	7.73E-04	1.13E-04	5.67E-05	5.58E-05	7.47E-05	2.00E-04	1.55E-03
Japan	–	2.82E-01	–	–	–	–	–	2.82E-01
Korea	8.49E-06	5.14E-05	5.55E-05	5.20E-04	5.60E-06	2.36E-05	1.19E-05	6.76E-04
Nigeria	–	1.05E-02	–	–	–	–	–	1.19E-02
Poland	3.87E-02	4.90E-01	9.00E-02	4.73E-02	1.07E-02	9.34E-02	1.00E-01	8.70E-01
Romania	4.12E-03	–	4.20E-04	1.00E-04	–	7.55E-05	2.82E-03	7.54E-03
USA	3.33E-02	4.73E-01	3.37E-02	1.16E-01	3.77E-02	4.30E-01	5.36E-01	1.66E+00
Total	7.66E-02	1.86E+00	1.25E-01	1.64E-01	4.85E-02	5.23E-01	6.42E-01	3.44E+00

Chr = chrysen, BaA = benzo[a]anthracene, BaP = benzo[a]pyrene, BkF = benzo [k]fluoranthene, BbF = benzo[b] fluranthene BghiP = benzo[g,h,i]perylene, DahA = dibenz[a,h]anthracene, IndP = indeno [1,2,3,c,d]pyrene.

lighter PAHs are more readily absorbed into the organic components of soil compared to heavier PAHs. This makes them more likely to travel greater distances from contamination sources and potentially contaminate coffee plant seeds [50]. Yebra-Pimentel et al. indicated that atmospheric pollutants originating from mines, factories, industries, and railways may facilitate the transfer of pollution from plants to the proposed soil-root-shoot transmission system, aligning with the findings of this study [51]. Duedahl-Olesen et al. in their research highlighted that the type of roasting, the brewing method, and the caffeine content in coffee are factors that can influence the levels of PAH across different countries. It has been observed that caffeine facilitates the extraction of PAH during the coffee brewing process, which explains the scarcity of caffeine-free coffee options available in Denmark [52]. Turaki Usman and colleagues have determined that the emission of vehicle exhaust, burning firewood in households, emissions from industries, and burning vegetation are significant contributors to PAH contamination in food [53].

Houessou and colleagues have found that the level of PAH in roasted coffee is influenced by the roasting process, specifically the temperature and duration. Roasting at higher temperatures can lead to the conversion of lower molecular PAHs to higher molecular weight PAHs, potentially impacting the overall PAH content in the coffee [54]. Shoaei et al. identified that environmental contamination, including atmospheric deposition, hydrocarbon-based materials, and root uptake, along with the activities of various industries, particularly those related to fossil fuels across different countries, significantly influences the presence of polycyclic aromatic hydrocarbons (PAHs) in consumable coffee [14]. Tarragona, Vyskocil et al. have pinpointed that the PAH content in the Chemical sector, residential area, and a zone dedicated to petrochemical processing stands at 476.2, 206.9, and 119.7 μg kg-1, respectively [55]. Kamal El-Deen and colleagues have pointed out that the levels of PAHs in coffee can vary depending on the contamination of the beans from urban runoff, industrial wastewater, or PAHs present in the air [56].

3.4. Health risk assessment

Food items tainted with harmful substances like PAHs can present a danger to human health. Studies have indicated that consuming PAH-contaminated foods contributes to 88 % of PAH exposure while inhaling PAHs makes up the remaining 12 % [57]. PAHs have been classified as a top-priority pollutant by the International Agency for Research on Cancer (IARC) because of their cancer-causing and mutation-inducing properties [58]. Multiple research studies have provided evidence of a correlation between being exposed to PAHs and the development of lung, respiratory system, and stomach cancers [59]. Tables 2 and 4 display crucial information on the cancer-causing and mutation-inducing dangers linked to PAHs found in processed cereals, measured in aP equivalent (μg/kg), across different nations. Although Finland has been identified as the foremost nation regarding carcinogenic risk, with Nigeria, India, Spain, Iran, Poland, Latvia, the United Kingdom, Saudi Arabia, and Turkey ranking subsequently, Nigeria leads in mutagenic risk, followed by the United Kingdom, Finland, Iran, Poland, Latvia, Turkey, India, Spain, and Saudi Arabia. Our research findings are in line with numerous studies that have investigated the carcinogenicity and risk of metastasis linked to different products. The 2011 study conducted by Alomirah and colleagues supports our results. We found that elevated levels of genotoxic PAHs were present in the vegetables and smoked foods commonly consumed by people of all ages in Kuwait, potentially heightening their vulnerability to cancer [60]. Processed cereals with varying levels of PAH concentrations may contribute to the disparities in cancer-related and mutation-inducing effects observed across different nations. This is because the risk of cancer and other health issues related to PAHs in processed cereals is less than 10-6. The detection of PAHs in processed cereals underscores the importance of regulatory agencies regularly evaluating and overseeing these products to minimize contaminants.

4. Conclusion

The present study indicated that the levels of PAHs varied across different countries and within coffee products. The risk assessment revealed there were carcinogenic or mutagenic risks of PAHs in most countries that can be due to environmental conditions, type of industries active mines, and food processing and cooking methods, therefore regular monitoring is necessary to reduce contaminants.

CRediT authorship contribution statement

Razieh Parvareshi Hamrah: Data curation, Conceptualization. **Alireza Rahimi:** Methodology. **Mohanna Yarahmadi:** Writing – original draft, Formal analysis. **Elaheh Talebi-Ghane:** Validation, Formal analysis. **Fereshteh Mehri:** Writing – review & editing, Writing – original draft, Visualization.

Declaration of competing interest

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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Data availability

Data will be made available on request.

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