ORIGINAL ARTICLE

Assessing the contamination levels of dried teas and their infusions by polycyclic aromatic hydrocarbons (PAHs)

Artur Ciemniak[1] · Kamila Kuźmicz[1] · Monika Rajkowska-Myśliwiec[1] · Maria Fernanda Cadena[2]

Abstract

The occurrence of 16 polycyclic aromatic hydrocarbons (PAHs) in 68 brands of teas, bought in Poland, was surveyed using ultrasonic extraction of dried teas and liquid–liquid extraction of infusions. The extracts were cleaned by solid phase extraction. The instrumental analysis was performed using gas chromatography coupled with mass spectrometry (GC–MS). The total content of 16 PAHs ($\sum$16PAHs) ranged from 41.5 to 2910.2 µg/kg in dried teas and from 52.9 to 2226.0 ng/L in infusions. Benzo(a)pyrene was found from below limit of quantification to 75.7 µg/kg in dried teas and from limit of detection to 18.7 ng/L in infusions. The least contaminated samples were herbal and fruit teas, while traditional black, green, red, and white teas, i.e. teas made of *Camellia sinensis,* were more polluted. Positive correlations between dried traditional teas and their infusions were observed. The mean transfer rates of $\sum$16PAHs from dried materials into water ranged from 2.4 to 25.3%. The total toxicity of the tested teas largely corresponded to the sum of 4 PAHs ($\sum$4PAHs) chosen by the European Food Safety Authority as indicator of PAHs in food. Estimated PAHs uptake and margin of exposure pointed to low health risks associated with drinking tea infusions.

Keywords PAHs · Polycyclic aromatic hydrocarbons · Tea · TEQ · MOE

1 Introduction

Polycyclic aromatic hydrocarbons (PAHs) are the group of organic compounds consisting of fused aromatic rings bound in various geometric configurations. Widespread in the environment, PAHs are by-products of reactions occurring in incomplete combustion of organic matter (pyrolysis). They are formed in homes and industry, particularly when high temperatures are involved. PAHs are produced by transport enterprises, household furnaces, uncontrolled waste combustion, and some heat treatment of food processing. The primary contamination source of PAHs for nonsmokers and people not exposed occupationally is foodstuffs. In general, the content of PAHs in unprocessed food depends on the level of environmental pollution (EFSA 2008; Singh et al. 2016).

Before deposition, gaseous and particle-bound PAHs may be transported over long distances (Simonich and Hites 1995), leading to the contamination of plants, including edible ones. The wax cuticle covering plant surfaces facilitates the adsorption of lipophylic air pollutants. Because they have particularly high surface areas, herb and tea leaves are thus easily contaminated with PAHs and other hazardous compounds.

Many PAHs have been found to be carcinogenic. Benzo(a)pyrene—the best-known PAH representative was classified by the international Agency for Research on Cancer (IARC 2010) as a human carcinogen. Compared to benzo(a)pyrene, the toxicity of other PAHs may be determined using toxic equivalent factors (TEF) (Nisbet and LaGoy 1992). The total toxicity of all PAHs determined in each sample may be expressed as the toxic equivalent TEQ. The TEQ is the total quotient of individual concentrations and TEF established for certain compounds.

The current EU regulation on the content of PAHs in foodstuffs, which specifies the maximum allowed content

✉ Artur Ciemniak
artur.ciemniak@zut.edu.pl

1 Department of Toxicology, Faculty of Food Sciences and Fisheries, West Pomeranian University of Technology, Papieża Pawła VI 3, 71-459 Szczecin, Poland

2 Pontificia Universidad Catolica del Ecuador, Av. 12 de Octubre 1076 y Roca, Quito, Ecuador

of benzo(a)pyrene and total 4PAHs in some foodstuffs, does not include any content of PAHs in teas. Howewer, the policymakers are cognizant that a number of goods still lack a specified maximum allowed level due to insufficient data. Commission Regulation (EU) No. 2015/1933 of 27 October 2015 (EC 2015) listed already-dried herbs, for which the maximum allowed BaP content may not exceed 10 μg/kg and total 4PAHs 50 μg/kg. Although herbs and teas are not completely interchangeable, these numbers can serve as a preliminary guideline.

Tea is the second most widely consumed beverage after water. Besides many beneficial effects, tea like other plant is unfortunately, not free of pollutants that may have adverse effects on human health. The relatively large surface area of tea leaves makes accumulating air pollutants significantly easier. It is therefore not surprising that pesticides, dioxins, furans and other contaminants have been reported in tea leaves (Fiedler et al. 2002; Hayward et al. 2015). Moreover, comparison of fresh and dried leaves, suggests that the manufacturing process may significantly increase PAHs levels in the end product; in particular, high amounts of PAHs are reported in tea manufactured with the use of smoke or heat, such as yerba mate, or some types of green and black tea (Lin and Zhu 2004; Kamangar et al. 2008; Ziegenhals et al. 2008; Schulz et al. 2014).

Although determining PAH levels in dried tea is relatively common, only a few studies have measured PAHs levels in tea infusions. Therefore, the main objective of this study was to determine the content of polycyclic aromatic hydrocarbons in dried tea and its infusions and to compare the results with EU legislation as well as with data obtained by other researchers.

2 Materials and methods

2.1 Sample collection

The analysis of polycyclic aromatic hydrocarbons in tea and its infusions was performed using 68 tea brands purchased on the Polish market (Szczecin) between 2002 and 2016. The study was based on traditional teas (37 brands), herbal teas (19 brands: chamomile, linden, hibiscus) and fruit teas (12 brands). The fruit teas were a mixture of herbs and fruits: hibiscus, apple, blackcurrant, chokeberry, black elder, rosehip, orange peel, lemon peel, pineapple, kiwi, and passion fruit. The largest group of test samples was comprised of black teas divided into three types: loose leaf tea (9 brands), granulated tea (3 brands), and tea bags (7 brands). Moreover, the analysis included loose leaf red tea (3 brands), loose leaf green tea (5 brands), green tea bags (5 brands), loose white tea (2 brands), and white tea bags (3 brands). Of each tea brand, three packages were purchased

from three different shops. Until the analysis, the tea was stored in its original packaging at room temperature, not longer than month, within the expiration date.

2.2 Sample preparation and chromatographic determination

The reagents used for analysis—hexane, dichloromethane, florisil, and anhydrous sodium sulphate (HPLC grade or analytical grade)—were purchased from Scharlau (Barcelona, Spain), Fluka (Buchs, Switzerland) and Polskie Odczynniki Chemiczne—POCH (Gliwice, Poland). Deuterated PAHs standards (Semivolatile Internal Standard Mix) and standard mixtures of 16 PAHs (EPA 610 PAH Mix and Polynuclear Aromatic Hydrocarbons Mix) were purchased from Sigma-Aldrich (Poznań, Poland).

PAHs were extracted from dried tea by ultrasonication with hexane, from infusion by liquid–liquid extraction by means of cyclohexane. The subsample (5 g) was transferred to 100 mL Erlenmeyer flasks and hexane (30 mL) was added. To take the recoveries into account, 50 μL of deuterated PAHs (32 μg/L) were added to each sample. The samples were then set aside for 24 h. Extraction was carried out for 30 min in an ultrasonic bath, then the solution was decanted. Another amount of hexane (20 mL) was added to a flask that was again put into an ultrasonic bath for 15 min. The content was filtered and washed twice with 10 mL of n-hexane. The obtained filtrate was concentrated up to 2 mL using a rotary evaporator. Infusions were prepared in a manner similar to household preparation. For this purpose, 8 g of tea were submerged in 1 L of boiling-hot tap water. Tea was brewed under cover for 10 min. Infusions were not filtered but were carefully decanted to obtain a clear solution. PAHs were extracted three times with cyclohexane (70, 30 and 15 mL). Extracts were filtered on anhydrous sodium sulphate. The obtained extracts were concentrated up to 2 mL using a rotary evaporator. The extracts were cleaned by solid phase extraction (SPE) using columns filled with 1 g of florisil (Ciemniak and Mocek 2010). The advantage of florisil is that it absorbs tannins and phenols that are found in significant amounts in teas, whereas PAHs can be successfully eluted and determined (Locatellia et al. 2014).

The analytical determination of 16PAHs in samples was performed by gas chromatography coupled with mass spectrometry (GC–MS) in an HP6890/5973 instrument equipped with a ZB-5MS column (30 m × 0.25 μm × 250 μm) using parameters previously described by Kuźmicz and Ciemniak (2018).

2.3 Quantitation method and quality assurance

All quantifications were made using external calibration curves and then recovery of deuterated standards were

calculated and used to correct the readings for 2- 3-, 4-, and 5-ring native compounds: naphthalene-d8 (NA D8) was used to adjust NA; acenaphthene-d10 (AC D10): ACL, AC and FL; phenanthrene-d10 (PHE D10): AN and PHE; chrysene-d12 (CHR D12): FA, PY, BaA, and CHR; benzo(a)pyrene-d12 (BaP D12): BbFA, BkFA, and BaP; perylene-d12 (Per D12): IP, DahA and BghiP.

The limit of detection (LOD) and limit of quantification (LOQ) were determined and calculated based on the data from the calibration curves (Kuźmicz and Ciemniak 2018). Analysis, including fortification experiment and recovery calculations, confirmed that the PAHs analysis conformed to the requirements set in Commission Regulation (EU) No. 836/2011 of 19 August 2011 (EC 2011) (Table 1).

Statistics were generated using Statistica 13 software (StatSoft Inc., Kraków, Poland). The significant differences between mean values of PAHs in different kinds of dried teas and their infusions were determined using analysis of variance (ANOVA) and Duncan's multiple range test at the significance level of $p < 0.05$. Furthermore, to describe the strength of a linear association between dried teas and their infusions, Pearson's correlation coefficient (r) was calculated.

3 Results and discussion

3.1 Polycyclic aromatic hydrocarbons in dried teas and tea infusions

In selected teas, 16 PAHs recommended by US EPA (1984) were determined (Fig. 1 and Table 2). The tests showed a very broad range of dried teas contamination with both the total PAHs and carcinogenic PAHs (Table 2). The presented results, similarly to other studies, revealed a typical PAHs profile with dominant non-toxic group (2–4 rings PAHs). Total 16 PAHs ranged from 41.5 to 2910.2 µg/kg, while $\sum$4PAHs ranged from 0.7 to 319.7 µg/kg. The average PAHs contents in all types of tea were 536.2 µg/kg ($\sum$16PAHs) and 58.9 µg/kg ($\sum$4PAHs). The least contaminated were teas containing hibiscus (average 113.9 µg/kg of PAHs) and fruits (149.8 µg/kg PAHs).

Other authors have reported similar values in herbal teas. Schlemitz and Pfannhauser (1997) detected PAHs at 13.41 and 140.4 µg/kg in fennel and mint teas, respectively. Londoño et al. (2015) found 16 PAHs in concentrations from 509.7 (black tea) to 2746.5 µg/kg (green tea) in Argentinian teas, Khiadani et al. (2013) from 138.9 to 2082.2 µg/kg in black Iranian teas, while Kamangar et al. (2008) reported 21 PAHs from 536 to 2906 µg/kg in yerba mate. Lower results for 28 PAHs were obtained by Roszko et al. (2018) in tea purchased in Poland: from 213.3 (white

tea) to 325.0 µg/kg (green tea). All the above-mentioned studies confirm considerable variation in levels of tea contamination. Two explanations account for such wide variations in the results: first, the environmental pollution of the area where tea plants are grown, and second, the technological processing of raw materials because many of them are dried using combustion gases (Lin and Zhu 2004). The most contaminated tea is mate tea, e.g., total 16 PAHs: 7536.33 µg/kg with 542.26 µg/kg of BaP (Schlemitz and Pfannhauser 1997). The high amount of PAHs were also found in lapsang souchong black tea which is roasted and smoked over resin-rich wood (Schulz et al. 2014). For each type of tea we found samples with a low total and carcinogenic PAHs content as well as samples that were significantly contaminated. The most diverse group in this studies was black tea (Table 2).

Also, the most toxic PAHs (EU 15 + 1 PAHs), in high concentrations were reported in teas, e.g., Schulz et al. (2014) determined EU 15 + 1 PAHs at 2200 µg/kg, including $\sum$4PAHs at 1700 µg/kg, and the maximum of BaP at 460 µg/kg in black tea, while in this study we found 319.74 µg/kg ($\sum$4PAHs). In our study BaP was detected in all the tested teas, with an average content of 2.5% of $\sum$16PAHs. The mean concentration of BaP ranged from 1.1 µg/kg in chamomile teas to 62.4 µg/kg in linden teas. Among the analyzed teas, only with regard to linden tea, statistical analysis revealed significant impact of benzo(a)pyrene concentration on the total PAH content. Its presence constituted on average 7.58% of total PAHs, while in the remaining ones it was found in the range 0.54–2.07%.

Based on the degree of contamination from low to high, dried teas can be arranged in the following order (average of $\sum$16PAHs): hibiscus (113.9 µg/kg) < fruit (149.8 µg/kg) < mint (184.7 µg/kg) < chamomile (195.1 µg/kg) < black (507.3 µg/kg) < red (769.7 µg/kg/) < linden (823.2 µg/kg) < green (932.0 µg/kg) < white (1149.9 µg/kg) tea. Taking into account the average PAHs content in all the traditional teas, Duncan's multiple range test revealed the least contamination in black teas, and the highest mean level in white tea. Significant differences ($p < 0.05$) were also observed between PAHs content in black and red teas compared to the green ones (Table 2).

The sum of these compounds in the fruit teas was significantly lower than in traditional teas ($p < 0.05$). One reason for this could be that herbal and fruit teas are not processed in the same manner as traditional teas. They are manufactured from dried leaves, flowers, and fruits of different plants such as linden, chamomile, mint, hibiscus, and fruit pieces. Additionally PAHs accumulation is facilitated by caffeine which is present in traditional tea leaves but absent in tested herbal and fruit teas (Lin and Zhu 2004; Navarro et al. 2009). Among the tested herbal
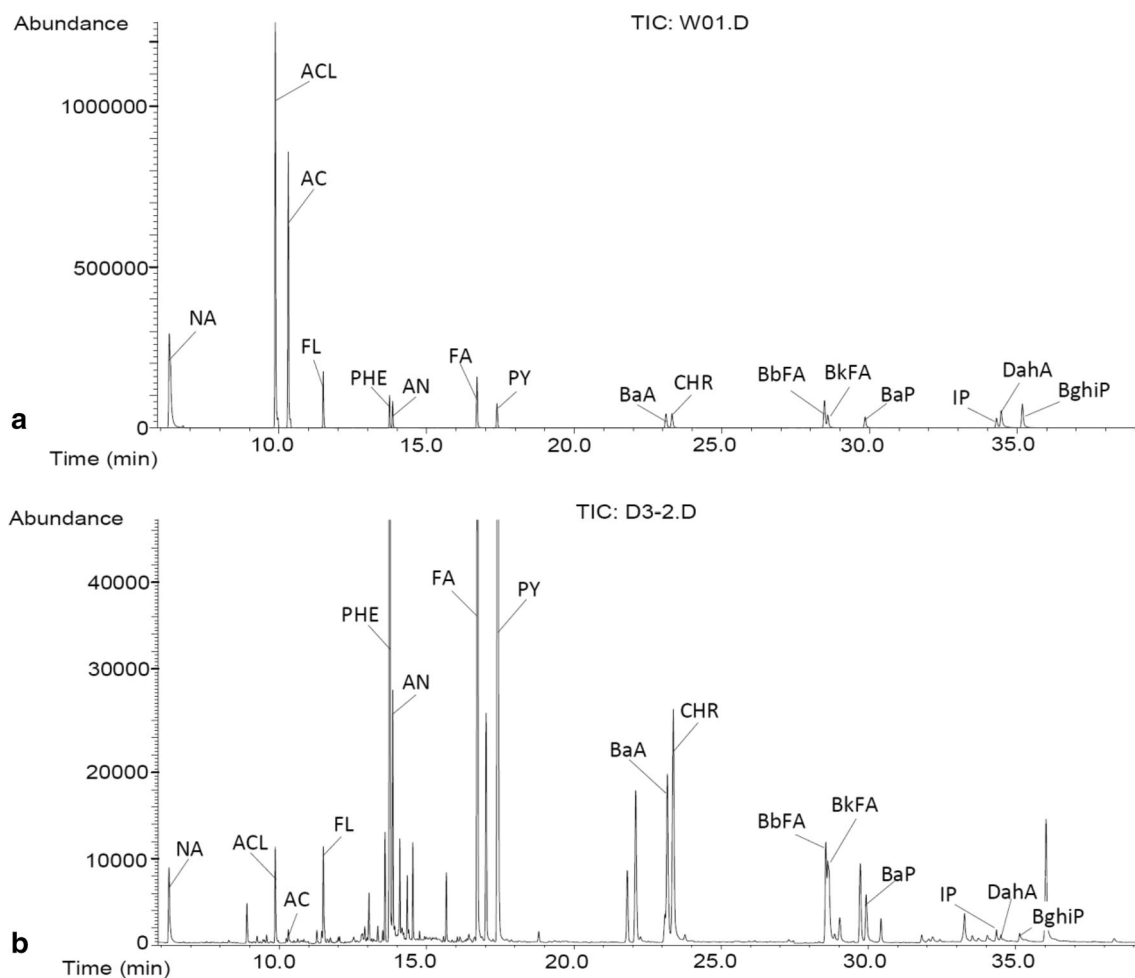
Table 1 Method validation parameters

Parameter	NA	ACL	AC	FA	PHE	AN	FL	PY	BaA[b]	CHR[b]	BbFA[b]	BkFA	BaP[b]	IP	D(ah)A	BghiP	Evaluation criteria (EC 2011)
Dried tea																	
Limit of detection (LOD) (μg/kg)	0.32	0.22	0.15	0.16	0.16	0.10	0.11	0.10	0.11	0.09	0.12	0.14	0.10	0.14	0.23	0.17	≤ 0.3
Limit of quantification (LOQ) (μg/kg)	0.97	0.66	0.46	0.49	0.47	0.31	0.32	0.31	0.37	0.28	0.37	0.41	0.29	0.42	0.7	0.52	≤ 0.9
Recovery (%)[a]																	
10 (μg/kg)	37.10	38.41	44.23	45.88	57.86	53.22	71.86	76.53	78.40	88.24	70.40	70.77	73.70	72.15	73.59	70.72	50–120
50 (μg/kg)	40.21	37.0	47.64	43.70	58.42	58.83	78.28	84.04	83.20	96.10	73.20	73.0	73.00	72.91	72.44	71.69	
HORRAT$_r$	1.0	1.3	0.8	0.8	0.7	0.7	0.7	0.6	0.7	0.7	0.8	0.8	0.7	0.7	0.8	0.7	< 2
Infusion																	
Limit of detection (LOD) (ng/L)	0.28	0.26	0.25	0.17	0.12	0.11	0.17	0.13	0.10	0.10	0.12	0.14	0.10	0.2	0.13	0.15	≤ 0.3
Limit of quantification (LOQ) (ng/L)	0.86	0.78	0.74	0.51	0.35	0.35	0.51	0.40	0.35	0.29	0.31	0.40	0.42	0.62	0.40	0.45	≤ 0.9
Recovery (%)[a]																	
0.5 (μg/L)	35.53	41.13	43.53	49.60	59.33	49.53	69.87	73.47	74.00	78.73	65.60	73.95	74.80	68.57	62.47	70.42	50–120
2 (μg/L)	43.33	38.33	41.31	47.27	56.00	57.07	83.65	80.77	89.40	104.70	77.33	82.84	82.60	73.80	73.55	81.08	
HORRAT$_r$	1.2	0.8	1.2	0.7	0.8	1.0	0.8	0.7	0.7	0.8	0.7	0.9	0.7	0.8	1.0	0.8	< 2

NA naphthalene, *ACL* acenaphthylene, *AC* acenaphthene, *FL* fluorene, *AN* anthracene, *PHE* phenanthrene, *FA* fluoranthene, *PY* pyrene, *BaA* benzo(a)anthracene, *CHR* chrysene, *BbFA* benzo(b)fluoranthene, *BkFA* benzo(k)fluoranthene, *BaP* benzo(a)pyrene, *IP* indeno(1,2,3-c,d)pyrene, *DahA* dibenzo(a,h)anthracene, *BghiP* benzo(g,h,i)perylene

[a] The results do not reflect adjustments made with the use of deuterated PAH standards

[b] PAHs listed in EC (2011); HORRAT$_r$: Horwitz ratio calculated according to EC (2011)

Assessing the contamination levels of dried teas and their infusions by polycyclic aromatic...

267

Fig. 1 Chromatograms of PAH standard: EPA 610 PAH Mix (**a**), black tea sample (**b**)

teas, we detected a significantly higher average concentration of $\sum$16PAHs in linden tea (823.2 µg/kg) including a significantly higher BaP content (62.4 µg/kg). This contamination may result from pollution of the environment where linden trees grow. They usually grow along roads, so their source of pollution is car fumes. The quality of the raw material is of great importance as well; e.g., teas made of the oldest leaves and even pieces of stalks, are also source of PAHs and other contaminants (Fiedler et al. 2002). White tea is not heavily processed, there is no direct contact with combustion gases, hence white tea should not be so heavily polluted. However, white tea is made of young, soft buds plucked in early spring, when the air is polluted from household heating. Moreover young leaves contain the highest amounts of lipophylic essential oils that make adsorbing PAHs easier. At low ambient temperatures, PAHs are easily deposited on the plants (Simonich and Hites 1995). In some manufacturing processes the leaves are roasted to give them their unique aroma. The high content of PAHs in green teas is undoubtedly associated with direct exposure to smoke (Fiedler et al. 2002).

The presented results show a typical PAHs profile with dominant non-toxic PAHs representatives such as PHE, AN, Flu and PY. Nevertheless, the TEQ value, describing approximate total toxicity of PAHs, depends mainly on PAHs having high TEF values. As a result, $\sum$4PAHs, i.e., BaA + CHR + BbFA + BaP, contained in 10.99% of total determined compounds, may in extreme cases decide over 95% of the TEQ (on average 59.34% of TEQ). The relationship between toxic equivalents expressed as $\sum$16TEQ and $\sum$4TEQ (Table 2) indicates that the total toxicity of the tested teas largely corresponded to the $\sum$4PAHs (from 23.58% of $\sum$16TEQ in mint teas up to 80.28% of $\sum$16TEQ in hibiscus teas).

The contamination of dried teas is reflected in the contamination of their infusions. The concentrations of all 16 PAHs in infusions varied from 52.9 ng/L in hibiscus tea bags to 2226.0 ng/L in white tea bags, with an average of 512.4 ng/L (Table 3). Most infusions contained BaP as well. In our study the most contaminated were infusions made of white tea, which contained on average 1511.9 ng/L (Σ16PAHs) and up to 8.2 ng/L of BaP. There were

Table 2 PAH levels (μg/kg) in different types of dried tea

Tea type	NA	ACL	AC	FL	PHE	AN	Flu	PY	BaA	CHR	BbFA	BkFA	BaP	IP	DBahA	BghiP	∑16PAH	∑4PAH	TEQ16	TEQ4
Traditional teas (Camellia sinensis)																				
Black (19 tea brands)																				
Mean	38.9	2.1	1.5	9.8	119.7	68.1	95.2	92.8	20.9	21.8	9.0	11.1	10.5[a]	2.1	1.7	2.2	507.3[ade]	62.2[ab]	24.7	13.7
Min	17.1	<LOQ	<LOQ	1.5	15.9	0.8	6.3	3.5	0.3	1.1	0.5	<LOQ	0.3	<LOD	<LOD	<LOD	79.8	3.4	0.6	0.5
Max	70.8	13.4	8.0	71.4	562.1	590.3	597.3	615.6	101.4	91.5	63.6	63.7	63.1	15.8	6.9	10.5	2910.2	319.7	118.9	80.6
Green (10 tea brands)																				
Mean	42.4	16.9	7.0	54.2	235.0	229.8	134.9	112.4	28.4	30.8	9.0	13.1	12.9[ab]	1.5	1.3	2.5	932.0[bce]	81.1[ab]	28.0	17.0
Min	18.8	0.6	0.8	6.1	47.0	3.2	6.3	33.1	<LOD	10.4	<LOD	2.2	1.6	<LOQ	<LOD	<LOD	210.6	18.1	8.7	2.9
Max	81.1	50.3	27.9	231.2	495.6	1165.5	408.3	335.0	60.6	60.5	28.2	31.5	30.9	4.6	2.4	8.0	1851.7	161.5	54.6	37.7
Red (3 tea brands)																				
Mean	22.5	5.0	5.8	29.6	243.4	201.6	89.9	95.3	16.4	17.3	6.0	14.6	11.7[ab]	4.7	2.1	3.8	769.7[abe]	51.3[ac]	29.2	14.1
Min	12.4	2.4	3.2	15.5	170.5	16.0	41.4	75.0	12.7	13.0	2.4	12.4	9.7	3.1	1.8	1.3	479.6	47.2	25.8	12.4
Max	42.1	7.6	7.2	41.3	297.8	312.5	147.2	118.0	19.7	21.5	12.4	18.9	14.8	5.7	2.4	6.0	949.8	58.9	34.8	17.3
White (5 tea brands)																				
Mean	60.3	40.4	4.0	23.3	372.1	92.6	220.0	213.8	30.4	30.7	9.6	19.9	17.2[b]	7.5	1.8	6.8	1149.9[c]	88.0[b]	35.1	21.5
Min	37.5	1.6	2.3	4.8	47.0	3.1	43.5	32.0	7.0	14.0	3.5	2.7	2.0	<LOD	<LOD	<LOD	233.9	28.3	5.0	3.8
Max	82.4	142.7	6.8	43.1	904.5	279.0	499.8	539.7	73.0	74.4	21.6	45.4	48.7	24.2	3.5	25.9	2572.0	206.1	82.9	57.8
Herbal teas																				
Mint (6 tea brands)																				
Mean	21.1	1.4	3.2	18.3	49.9	11.9	39.0	13.6	2.7	8.4	1.7	3.5	2.1[a]	5.4	1.5	1.0	184.7[df]	14.9[cd]	11.2	2.7
Min	5.0	0.3	0.9	7.8	17.0	2.1	19.7	<LOD	0.5	1.9	<LOD	<LOQ	<LOQ	<LOD	<LOD	<LOD	103.6	4.6	0.3	0.1
Max	50.4	2.6	8.2	37.1	76.1	42.0	118.4	22.9	5.6	20.5	4.3	6.2	5.3	20.2	3.6	2.7	263.0	21.0	22.1	5.9
Chamomile (7 tea brands)																				
Mean	37.2	1.5	11.7	21.0	21.9	66.0	18.1	10.6	0.9	2.9	0.7	0.7	1.1[c]	0.4	0.4	0.3	195.1[df]	5.5[b]	4.1	1.2
Min	10.4	<LOQ	1.3	4.3	4.7	1.2	10.0	5.6	<LOD	0.8	<LOD	<LOD	<LOQ	<LOD	<LOD	<LOD	75.3	1.7	0.7	<LOD
Max	76.6	5.3	39.1	53.4	54.9	250.6	29.7	15.5	3.2	6.5	2.6	2.2	3.8	1.4	1.1	0.8	437.5	13.2	10.0	3.9
Hibiscus (4 tea brands)																				
Mean	18.3	0.8	3.1	14.9	23.1	24.6	13.5	8.1	0.6	2.0	1.9	0.8	1.5[c]	0.6[A]	–	–	113.9[f]	6.0[d]	2.2	1.8
Min	4.3	<LOQ	<LOQ	3.2	0.9	0.8	7.8	5.0	<LOD	1.0	<LOD	<LOQ	0.3	<LOD	<LOD	<LOD	41.5	4.3	0.8	0.6
Max	35.6	1.9	4.4	26.5	53.7	57.4	21.3	10.7	1.1	2.9	3.5	2.5	3.0	0.6	<LOQ	<LOQ	145.6	7.6	4.1	3.4
Linden (2 tea brands)																				
Mean	8.8	9.5	4.0	30.4	153.7	10.6	193.5	112.8	29.6	72.4	49.2	48.2	62.4[d]	28.5	7.9	1.8	823.2[e]	213.5[e]	118.9	71.0
Min	8.3	4.5	1.1	19.3	114.1	8.7	173.0	99.5	11.9	62.9	48.6	32.8	49.1	14.2	3.3	1.3	705.1	199.1	87.3	59.6
Max	9.2	14.5	6.9	41.4	193.4	12.6	213.9	126.0	47.2	81.9	49.8	63.6	75.7	42.7	12.6	2.4	941.3	228.0	150.5	82.4
Fruit teas (12 tea brands)																				
Mean	23.6	4.0	5.8	14.6	34.9	32.0	13.1	11.5	1.5	3.6	1.5	2.0	1.2[c]	0.3	–	0.3	149.8[df]	7.8[d]	2.2	1.6
Min	3.7	<LOQ	<LOD	1.6	<LOD	1.4	<LOQ	<LOD	<LOD	0.4	<LOD	<LOD	0.3	<LOD	<LOD	<LOD	43.0	0.7	0.5	0.3

Table 2 (continued)

Tea type	NA	ACL	AC	FL	PHE	AN	Flu	PY	BaA	CHR	BbFA	BkFA	BaP	IP	DBahA	BghiP	$\sum$16PAH	$\sum$4PAH	TEQ16	TEQ4
Max	47.2	17.8	27.9	58.9	89.4	106.5	59.8	46.7	7.6	13.1	6.2	9.5	2.8	1.3	<LOQ	1.2	307.9	27.3	5.1	4.1
Mean	30.3	9.1	5.1	24.0	139.3	81.9	90.8	74.6	14.6	21.1	9.8	12.7	13.4	6.3	1.9	2.1	536.2	58.9	28.4	16.1

Significant differences in $\sum$16PAHs, $\sum$4PAHs and BaP content between tea types: means sharing the same letters were not significantly different within a column (p < 0.05, Duncan's test comparison of means)

TEQ16 TEQ calculated for $\sum$16PAHs, *TEQ4* TEQ calculated for $\sum$4PAHs, $\sum$*4PAHs* [BaA + CHR + BbFA + BaP], – all results below LOQ

[A] Only one result above LOQ

statistically significant correlations between the sum of PAHs in dried black teas and their concentration in infusions (black, r = 0.87; green, r = 0.69; white, r = 0.75), whereas such correlations were not reported for herbal and fruit teas. This was clearly demonstrated in the case of linden tea, where the dried product was heavily contaminated, while its infusions contained relatively little PAHs. This discrepancy confirms there is no obvious relationship between the contamination level of dried herbal and fruit tea and its infusion. The level itself depends on parameters such as type and composition of tea from which the infusion was made. This finding suggests that the composition of tea leaves (*Camellia sinensis*) facilitates penetration of PAHs into an infusion.

Similarly to dried tea, the light PAHs (2–4 rings) were also dominant in infusions (Fig. 2). They are compounds that are relatively well soluble in water. A similar relationship was also noticed by Rascón et al. (2019), who found light PAHs in range from 0.55 to 4800 ng/L in almost all samples, while BaP was detected at relatively high contents in two tea samples: 20 and 180 ng/L. Lin et al. (2005) found only light PAHs whereas heavy (5–6 rings) PAHs were not detected. The present study showed that the light PAHs represented 98.5% of all determined PAHs. More toxic compounds—called heavy PAHs (5–6 rings)—were transferred to infusions in trace amounts or were absent. On average, the contribution of heavy PAHs in infusions was 1.5%, whereas that of $\sum$4PAHs was 3.18% of all the PAHs. Similarly to dried tea, these compounds ($\sum$4PAHs) significantly affected the TEQ value (53.6%) in infusions. Girelli et al. (2017) determined a similarly high share of light PAHs in infusions, i.e. 63% of 3-ring PAHs, 29% of 4-ring PAHs, 7% of 5-ring PAHs, and 1% of 6-ring PAHs. In turn, Khiadani et al. (2013) detected only the presence of 2- to 4-ring PAHs, both in dried tea and its infusions.

It is not just solubility in water that determines the amount of PAHs transferred from dried tea to infusion. Infusions contain compounds (e.g., essential oils) that may significantly increase their solubility in water. Moreover, PAHs are accumulated easily on the surface of solid bodies. In this study, the infusions were prepared exactly as for drinking, hence they were not filtered before tests and only the clear infusion was decanted. Therefore, each infusion contained not only dissolved compounds but also those transferred with the suspension (dust) from teas or herbs. We have found that, on average, 16.93% of PAHs were present in the infusion prepared using the described method (Table 4).

Roszko et al. (2018) obtained similar results: they reported 18% transfer of $\sum$28PAHs into infusion. In the case of $\sum$4PAHs, we observed transfer of 8.61%. That is more than found by Lin and Zhu (2004), who observed

Table 3 PAH levels (ng/L) in tea infusions

Tea type	NA	ACL	AC	FL	PHE	AN	Flu	PY	BaA	CHR	BbFA	BkFA	BaP	IP	DBahA	BghiP	∑16PAH	∑4PAH	TEQ16	TEQ4
Traditional teas (*Camellia sinensis*)																				
Black (19 tea brands)																				
Mean	113.9	9.7	3.3	13.0	218.5	15.0	86.8	85.9	7.7	9.6	3.5	2.4	3.2[abc]	3.3	0.3	2.6	578.6[a]	24.0[ac]	7.3	4.4
Min	17.0	<LOQ	<LOQ	2.3	19.5	0.6	12.6	17.7	1.0	1.5	0.6	0.3	<LOQ	<LOD	<LOD	<LOD	106.1	5.3	0.6	0.2
Max	360.4	59.7	9.8	56.5	650.4	61.3	346.7	382.2	32.7	36.4	12.5	11.1	18.7	35.7	1.1	15.3	1748.4	98.8	33.2	23.4
Green (10 tea brands)																				
Mean	94.9	15.7	5.7	26.6	286.2	43.8	134.5	112.7	6.6	9.7	2.7	2.0	2.0[ad]	0.8	0.3	0.9	745.0[a]	21.0[ab]	6.0	3.1
Min	7.1	<LOD	<LOD	2.4	62.0	5.0	35.5	29.7	2.3	4.5	0.7	0.5	<LOQ	<LOD	<LOD	<LOQ	210.2	7.5	1.5	0.3
Max	340.1	57.3	25.4	76.1	611.4	194.8	366.1	294.5	18.5	17.4	6.1	4.3	9.1	1.9	1.1	2.0	1496.3	46.8	18.5	11.3
Red (3 tea brands)																				
Mean	51.2	9.7	9.4	42.6	449.6	22.4	110.8	92.6	5.9	7.7	2.7	1.8	1.8[ad]	2.3[A]	<LOD	1.5	811.9[a]	18.1[abd]	4.1	2.7
Min	44.2	1.3	1.6	13.6	292.5	15.1	81.9	70.3	3.1	5.0	1.2	1.2	1.0	<LOD	<LOD	1.0	539.0	10.9	2.4	1.5
Max	60.3	17.7	15.3	72.1	623.2	30.0	143.1	116.6	7.4	9.8	5.0	2.2	2.6	2.3	<LOD	2.0	1077.5	23.2	5.4	3.9
White (5 tea brands)																				
Mean	140.9	204.0	9.5	53.3	599.4	52.4	217.0	194.9	9.5	12.4	6.5	3.0	4.4[b]	2.1	0.3	2.3	1511.9[c]	32.8[c]	10.1	6.2
Min	85.7	9.6	5.2	14.7	131.4	10.2	42.7	40.3	4.6	5.3	1.7	1.4	1.0	<LOD	<LOQ	<LOQ	526.6	13.8	2.5	1.7
Max	244.5	512.5	15.8	125.4	1126.3	101.9	361.7	308.6	13.6	18.7	9.8	4.5	8.2	3.5	1.1	4.9	2226.0	48.2	16.5	10.7
Herbal teas																				
Mint (6 tea brands)																				
Mean	58.0	1.5	2.5	14.9	67.2	2.7	16.6	14.3	1.3	2.5	1.1	0.6	0.4[d]	0.3	0.6[A]	0.4	184.6[b]	5.2[e]	3.8	0.7
Min	<LOQ	<LOQ	<LOD	3.0	20.4	1.8	9.2	5.0	0.6	1.3	<LOD	0.4	<LOD	<LOQ	<LOQ	0.5	83.6	3.5	0.5	0.2
Max	119.0	4.4	5.1	36.4	124.0	3.8	32.6	32.6	2.7	4.3	2.4	1.1	0.6	1.0	0.6	0.9	345.1	9.3	4.5	1.1
Chamomile (7 tea brands)																				
Mean	78.1	4.3	1.2	14.9	81.3	6.4	33.0	27.2	2.2	3.0	0.9	0.6	0.6[d]	0.3	0.8[A]	0.2	254.6[b]	6.6[e]	4.6	0.9
Min	38.2	<LOQ	<LOQ	3.6	20.0	0.5	5.4	3.5	<LOQ	0.4	<LOQ	<LOD	<LOD	<LOD	<LOD	<LOD	107.8	0.4	0.1	<0.01
Max	162.3	20.2	2.9	25.9	243.3	32.4	145.9	126.1	10.5	11.2	4.6	3.1	3.0	0.9	0.8	0.7	788.4	29.3	9.4	4.6
Hibiscus (4 tea brands)																				
Mean	87.1	1.5	8.3[A]	7.7	41.8	1.0	12.9	12.3	0.8	2.8	1.0	0.4	0.4[d]	1.1[A]	–	–	179.1[b]	5.0[e]	0.9	0.6
Min	28.0	<LOQ	<LOQ	2.6	12.6	0.5	4.2	2.4	0.4	1.2	0.4	<LOD	<LOD	<LOQ	<LOD	<LOD	52.9	2.5	0.2	0.2
Max	258.3	5.2	1.9	13.2	69.4	1.6	21.8	26.8	1.5	5.9	2.1	1.0	1.2	1.1	<LOQ	<LOQ	373.5	10.7	2.0	1.6
Linden (2 tea brands)																				
Mean	30.8	1.9	1.9[A]	13.6	57.7	2.5	22.4	11.3	1.2	3.2	1.8	2.7	1.2[cd]	1.0[A]	–	–	153.2[b]	7.5[de]	2.0	1.5
Min	22.5	1.2	<LOQ	10.4	42.1	2.1	15.3	11.1	0.9	1.2	1.6	<LOD	<LOD	<LOD	<LOD	<LOD	127.2	4.1	0.9	0.8
Max	39.1	2.5	1.9	16.8	76.2	2.9	29.5	11.5	1.5	5.3	2.1	4.9	1.8	1.0	<LOQ	<LOQ	179.2	10.8	3.0	2.3
Fruit teas (12 tea brands)																				
Mean	66.5	3.7	4.6	16.1	54.5	2.9	18.8	13.3	1.5	3.2	2.7	2.7	0.7[d]	0.4	–	0.5	192.5[b]	8.1[de]	1.7	1.1
Min	20.1	<LOQ	<LOQ	3.4	30.2	1.1	7.0	4.7	<LOQ	0.8	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	96.9	1.5	0.3	0.1

Table 3 (continued)

Tea type	NA	ACL	AC	FL	PHE	AN	Flu	PY	BaA	CHR	BbFA	BkFA	BaP	IP	DBahA	BghiP	∑16PAH	∑4PAH	TEQ16	TEQ4
Max	208.0	15.5	38.0	36.8	100.0	7.1	33.3	32.7	4.0	6.7	8.2	16.3	2.3	1.5	<LOQ	1.6	416.9	17.2	4.3	3.6
Mean	80.1	28.0	5.2	22.5	206.2	16.6	72.5	62.7	4.1	6.0	2.5	1.8	1.6	1.2	0.2	0.9	512.4	14.3	4.5	2.4

Significant differences in ∑16PAHs, ∑4PAHs and BaP content between tea types: means sharing the same letters were not significantly different within a column (p < 0.05, Duncan's test comparison of means)

TEQ16 TEQ calculated for ∑16PAHs, *TEQ4* TEQ calculated for ∑4PAHs, ∑*4PAHs* [BaA + CHR + BbFA + BaP], – all results below LOQ

[A]Only one result above LOQ
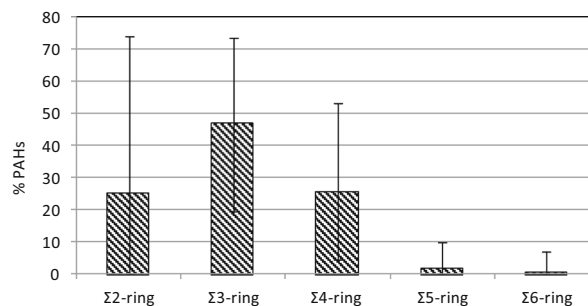
Fig. 2 Profile of 2, 3, 4, 5 and 6 rings PAHs (mean, minimum, maximum) for tea infusions

PAHs transfer from dried tea to infusions in the range of 4.45–10.8%. Much lower transfers of the ∑4PAHs (< 2%) were observed by Zachara et al. (2018), and Duedahl-Olesen et al. (2015) (2.3%). On the other hand, Pincemaille et al. (2014) noted very high release rates of ∑4PAHs into infusions (82–123%). They suggested that because most PAHs are deposited on the surface of the tea leaves, they may therefore migrate easily into infusions. Moreover, essential oils present in teas may increase the affinity of PAHs for the aqueous infusions.

Transfer of PAHs to infusion depends on a number of parameters, such as type of tea, brewing time, and water-to-tea proportion, as well as whether the infusion is prepared in an open or covered cup (Lin et al. 2005). It is generally low, but from slightly polluted raw material containing less than 100 μg/kg of PAHs, over 70% of PAHs may diffuse to infusion (Ciemniak and Mocek 2010). Therefore, PAHs levels in infusions, like those in dried tea, may change significantly, which has been shown in other authors' findings (Bishnoi et al. 2005; Lin et al. 2005).

3.2 Health risk evaluation

The average annual consumption of tea per person in Poland is 600 g (CSO 2018). That means the statistical polish consumer can prepare 300 glasses (250 mL) of tea in the manner given in the present study. Based on the maximum determined PAHs concentrations in tea infusions (the worst case scenario), calculated for ∑16PAH (2226.0 ng/L, white tea), ∑4PAH (98.8 ng/L, black tea) and BaP (18.1 ng/L, black tea) (Table 3), the uptake of them by an adult person (60 kg bodyweight [bw]) consuming 1 glass of tea was as follows: 9.28, 0.41 and 0.078 ng/kg bw. In addition, the average BaP/∑4PAH ratio for tested teas was 11.2%, with the maximum value for green tea (19.4%).

We also calculated the Margins of Exposure (MOEs) (EFSA 2008), using the highest concentrations of BaP and ∑4PAHS in the tested group of teas, benchmark dose

Table 4 Transfer rate (%) of PAHs during tea brewing

Tea type	NA	ACL	AC	FL	PHE	AN	Flu	PY	BaA	CHR	BbFA	BkFA	BaP	IP	DBahA	BghiP	∑16PAH	∑4PAH
Traditional teas (*Camellia sinensis*)																		
Black (19 tea brands)																		
Mean	37.7	68.0	49.2	22.8	34.4	18.6	22.1	26.6	13.0	13.2	20.9	6.6	7.9	20.8	4.6	24.7	20.8	12.1
Min	6.3	3.3	–	4.3	7.5	0.5	3.0	3.1	0.4	0.9	0.4	–	–	–	–	–	6.3	0.5
Max	114.4	109.8	111.2	62.7	81.6	101.7	103.2	114.4	76.9	94.9	105.2	27.5	65.1	63.0	8.8	113.5	55.2	57.5
Green (10 tea brands)																		
Mean	28.3	25.0	31.1	9.2	21.8	13.6	24.3	16.0	4.9	6.0	9.1	4.6	3.6	10.6	7.0	5.6	11.7	5.7
Min	1.1	–	–	1.0	5.1	0.3	7.5	5.5	0.5	1.2	0.8	0.2	0.8	–	–	–	4.7	0.7
Max	81.1	107.4	119.0	22.7	62.7	58.5	93.3	65.0	14.2	12.1	34.6	24.5	10.4	16.1	10.5	12.6	21.7	14.6
Red (3 tea brands)																		
Mean	39.2	20.3	17.7	16.4	22.8	4.7	21.8	12.3	4.4	5.6	9.5	1.5	1.9	5.28[A]	–	8.9	13.4	4.4
Min	14.5	6.6	6.3	11.0	20.7	1.0	9.5	9.6	3.0	4.8	1.9	1.2	1.2	–	–	2.0	10.8	2.9
Max	60.9	28.9	27.1	21.8	26.2	11.8	43.2	15.7	5.5	7.0	20.6	1.9	2.2	5.28	–	19.6	15.3	5.3
White (5 tea brands)																		
Mean	30.3	76.0	30.6	30.9	25.9	20.5	20.4	15.0	5.9	6.0	11.3	5.2	6.6	7.8	2.8	18.3	19.9	6.1
Min	18.8	44.9	18.3	18.3	12.9	2.2	5.8	5.4	2.3	2.8	3.4	1.1	1.9	–	1.6	–	10.8	2.9
Max	41.3	114.3	49.0	46.3	34.9	41.8	55.9	28.4	12.6	9.8	24.5	13.2	13.5	18.5	4.0	45.3	25.4	10.1
Herbal teas																		
Mint (6 tea brands)																		
Mean	76.2	35.4	20.8	15.2	22.3	8.3	8.2	11.9	9.1	6.1	4.5	2.3	2.8	1.1	2.0[A]	9.6	13.6	5.3
Min	–	–	–	2.0	3.6	0.6	1.0	6.2	2.8	0.8	–	0.8	–	–	–	8.4	5.1	2.9
Max	117.8	99.0	37.1	58.2	48.9	19.0	18.3	21.9	15.7	13.4	9.5	6.3	5.9	1.5	2.0	10.7	22.7	9.6
Chamomile (7 tea brands)																		
Mean	34.7	40.5	12.1	17.1	61.3	28.2	21.7	27.7	21.3	10.6	15.1	11.7	17.7	11.3	7.8[A]	1.3	22.6	10.5
Min	7.8	–	–	2.8	4.6	0.1	4.8	5.7	–	2.8	–	–	–	4.0	–	10.3	3.4	2.8
Max	61.5	113.6	28.7	38.6	116.5	113.8	80.9	104.7	41.2	21.6	22.6	17.9	40.6	18.1	7.8	12.3	62.1	27.9
Hibiscus (4 tea brands)																		
Mean	66.6	38.3	23.5[A]	10.1	34.5	4.3	15.6	24.6	14.0	17.6	6.6	6.1	23.3	22.9[A]	–	–	22.8	10.3
Min	26.9	–	–	1.2	9.6	0.2	2.4	3.5	6.3	9.1	4.7	5.3	–	–	–	–	4.8	4.3
Max	118.4	59.8	23.5	20.5	93.7	9.8	35.0	67.3	26.6	35.8	7.9	6.9	33.3	22.9	–	–	38.8	19.8
Linden (2 tea brands)																		
Mean	44.6	4.1	3.4[A]	7.0	5.5	3.1	1.5	1.3	0.9	0.6	0.5	1.0	0.2	0.9[A]	–	–	2.4	0.5
Min	30.5	1.0	–	3.1	2.7	2.1	0.9	1.1	0.2	0.2	0.4	0.1	0.1	–	–	–	1.7	0.2
Max	58.6	7.1	3.4	10.9	8.4	4.1	2.1	1.5	1.6	1.1	0.5	1.9	0.3	0.9	–	–	3.2	0.7
Fruit teas (12 tea brands)																		
Mean	43.0	15.0	15.3	34.8	18.9	8.8	22.7	24.4	12.2	19.4	16.0	19.4	16.5	12.6	–	6.6	25.3	22.7

Table 4 (continued)

Tea type	NA	ACL	AC	FL	PHE	AN	Flu	PY	BaA	CHR	BbFA	BkFA	BaP	IP	DBahA	BghiP	$\sum$16PAH	$\sum$4PAH
Min	7.9	–	–	3.2	4.2	0.2	4.3	–	–	3.6	–	–	–	5.5	–	–	4.6	2.3
Max	114.6	23.8	62.5	114.2	40.6	54.5	44.5	53.0	27.2	56.0	27.3	52.9	45.4	17.8	–	9.5	71.7	61.5
Mean	44.5	35.9	25.3	18.2	27.5	12.2	17.6	17.8	9.5	9.5	10.4	6.5	8.9	10.7	4.8	10.7	16.9	8.6

$\sum$*4PAHs* [BaA + CHR + BbFA + BaP], – results below LOQ

[A] Only one result above LOQ

lower confidence limit (BMDL$_{10}$) values for BaP (0.07 mg/kg bw/day), and $\sum$4PAHS (0.34 mg/kg bw/day). The obtained MOEs for BaP of 897,000 and $\sum$4PAHs of 830,000 differed from those reported by Roszko et al. (2018) at 700,000 and 400,000, respectively. According to the EFSA, health concerns associated with dietary exposure to PAHs can occur at MOE values close to or less than 10,000. Based on our calculations and those of Roszko et al. (2018), we may conclude that consumer exposure to PAHs via tea infusions is very low and safe for health.

4 Conclusions

In this study, we determined the PAHs content in dried teas and their infusions. PAHs content in tested dried teas varied significantly. While brewing tea, on average 16.93% of total PAHs was released into the infusion. Statistically significant correlations between the content of $\sum$16PAHs in dried tea and their infusions were found for black, green, and white teas. However, there were no such relationships for herbal and fruit teas.

The toxicity expressed with TEQs depended mainly on the content of compounds belonging to the group of heavy PAHs. All types of traditional teas had a higher average amount of $\sum$4PAHs as compared to the limit specified for herbs (EC 2015). In the group of herb and fruit teas, only in the case of linden tea did the content of $\sum$4PAHs arouse toxicological concerns. The maximum allowed amount of BaP (10 µg/kg) was exceeded in 17 analysed brands of tea. BaP concentrations in infusions of two types of black teas exceeded the maximum level (10 ng/L) specified for drinking water (EC 1998).

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

Bishnoi NR, Mehta U, Sain U, Pandit GG (2005) Quantification of polycyclic aromatic hydrocarbons in tea and coffee samples of Mumbai City (India) by high performance liquid chromatography. Environ Monit Assess 107:399–406

Ciemniak A, Mocek K (2010) Polycyclic aromatic hydrocarbons in tea and tea infusions. Rocz PZH 61(3):243–248

CSO, Central Statistical Office (2018) Statistical yearbook of the Republic of Poland 2018. Federal Statistical Office, Warszawa

Duedahl-Olesen L, Navaratnam MA, Jewula J, Jensen AJ (2015) PAH in some brands of tea and coffee. Polycyl Aromat Comp 35:74–90

EC (European Commission) (1998) Council Directive 98/83/EC of 3 November 1998 on the quality of water intended for human consumption. Off J Eur Union L 330:32–54

EC (European Commission) (2011) Commission Regulation (EU) No 836/2011 of 19 August 2011 amending Regulation (EC) No 333/2007 laying down the methods of sampling and analysis for the official control of the levels of lead, cadmium, mercury, inorganic tin, 3-MCPD and benzo(a)pyrene in foodstuffs. Off J Eur Union L 215:9–16

EC (European Commission) (2015) Commission Regulation (EU) No. 2015/1933 of 27 October 2015 amending Regulation (EC) No 1881/2006 as regards maximum levels for polycyclic aromatic hydrocarbons in cocoa fibre, banana chips, food supplements, dried herbs and dried spices. Off J Eur Union L 282:11–13

EFSA, European Food Safety Authority (2008) Scientific opinion of the panel on Contaminants in the Food Chain on a request from the European Commission on Polycyclic Aromatic Hydrocarbons in Food. Question No EFSA-Q-2007-136. EFSA J 724:1–114. http://www.efsa.europa.eu/sites/default/files/scientific_output/files/main_documents/724.pdf. Accessed 20 June 2017

Fiedler H, Cheung CK, Wong MH (2002) PCDD/PCDF, chlorinated pesticides and PAH in Chinese teas. Chemosphere 46:1429–1433

Girelli AM, Apriceno A, Tarola AM, Tortora F (2017) Determination of polycyclic aromatic hydrocarbons in tea infusions samples by high performance liquid chromatography with fluorimetric detection. J Food Qual 2017:1–4

Hayward DF, Wong JW, Park HY (2015) Determinations for pesticides on black, green, oolong, and white teas by gas chromatography triple-quadrupole mass spectrometry. J Agric Food Chem 63:8116–8124

IARC (2010) Monographs on the evaluation of carcinogenic risks to humans, some non-heterocyclic polycyclic aromatic hydrocarbons and some related exposures IARC (International Agency for Research on Cancer), Lyon. http://monographs.iarc.fr/ENG/Monographs/vol92/mono92.pdf. Accessed 02 Jan 2018

Kamangar F, Schantz MM, Abnet CC, Fagundes RB, Dawsey SM (2008) High levels of carcinogenic polycyclic aromatic hydrocarbons in mate drinks. Cancer Epidemiol Biomark 17(5):1262–1268

Khiadani M, Amin MM, Beik FM, Ebrahimi A, Farhadkhani M, Mohammadi-Moghadam F (2013) Determination of polycyclic aromatic hydrocarbons concentration in eight brands of black tea which are used more in Iran. Int J Environ Health Eng 2(3):40–45

Kuźmicz K, Ciemniak A (2018) Assessing contamination of smoked sprats (Sprattus sprattus) with polycyclic aromatic hydrocarbons (PAHs) and changes in its level during storage in various types of packaging. J Environ Sci Health B 53(1):1–11

Lin D, Zhu L (2004) Polycyclic aromatic hydrocarbons: pollution and source. Analysis of black tea. J Agric Food Chem 52:8268–8271

Lin D, Tu Y, Zhu L (2005) Concentration and health risk of polycyclic aromatic hydrocarbons in tea. Food Chem Toxicol 43:41–48

Locatellia M, Forcuccia L, Sciascia F, Cifellia R, Ferronea V, Carlucci G (2014) Extraction and detection techniques for PAHs determination in beverages: a review. Curr Chromatogr 1:122–138

Londoño VAG, Reynoso CM, Resnik S (2015) Polycyclic aromatic hydrocarbons (PAHs) survey on tea (Camellia sinensis) commercialized in Argentina. Food Control 50:31–37

Navarro RP, Ishikawa H, Morimoto K, Tatsumi K (2009) Enhancing the release and plant uptake of PAHs with a water-soluble purine alkaloid. Chemosphere 76:1109–1113

Nisbet ICT, LaGoy PK (1992) Toxic equivalency factors (TEFs) for polycyclic aromatic hydrocarbons (PAHs). Regul Toxicol Pharm 16:290–300

Pincemaille J, Schummer C, Heinen E, Moris G (2014) Determination of polycyclic aromatic hydrocarbons in smoked and non-smoked black teas and tea infusions. Food Chem 145:807–813

Rascón AJ, Azzouz A, Ballesteros E (2019) Use of semi-automated continuous solid-phase extraction and gas chromatography-mass spectrometry for the determination of polycyclic aromatic hydrocarbons in alcoholic and non-alcoholic drinks from Andalucía (Spain). J Sci Food Agric 99:1117–1125

Roszko M, Kamińska M, Szymczyk M, Jędrzejczak R (2018) Dietary risk evaluation for 28 polycyclic aromatic hydrocarbons (PAHs) in tea preparations made of teas available on the Polish retail market. J Environ Sci Health B 53(1):25–34

Schlemitz S, Pfannhauser W (1997) Supercritical fluid extraction of mononitrated polycyclic aromatic hydrocarbons from tea—correlation with the PAH concentration. Zeitschrift für Lebensmitteluntersuchung und Forschung A 205:305–310

Schulz CM, Fritz H, Ruthenschrör A (2014) Occurrence of 15 + 1 EU priority polycyclic aromatic hydrocarbons (PAH) in various types of tea (Camellia sinensis) and herbal infusions. Food Addit Contam A 31(10):1723–1735

Simonich SL, Hites RA (1995) Organic pollutant accumulation in vegetation. Environ Sci Technol 29(12):2905–2913

Singh L, Varshney JG, Agarwal T (2016) Polycyclic aromatic hydrocarbons' formation and occurrence in processed food. Food Chem 199:768–781

US EPA (1984) Health effects assessment of polycyclic aromatic hydrocarbons (PAHs). EPA 540/1-86-013. Cincinnati OH: Environmental Criteria and Assessment Office. http://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=2000FD6E.pdf. Accessed 11 May 2017

Zachara A, Gałkowska D, Juszczak L (2018) Contamination of tea and tea infusion with polycyclic aromatic hydrocarbons. Int J Environ Res Public Health 15(1):45–60

Ziegenhals K, Jira W, Speer K (2008) Polycyclic aromatic hydrocarbons (PAH) in various types of tea. Eur Food Res Technol 228:83–91